Photogrammetry: An Available Surface Characterization Tool for Solar Concentrators, Part I: Measurements of Surfaces

Close range photogrammetry is a sensing technique that allows the three-dimensional coordinates of selected points on a surface of almost any dimension and orientation to be assessed. Surface characterisations of paraboloidal reflecting surfaces at the ANU using photogrammetry have indicated that three-dimensional coordinate precisions approaching 1:20,000 are readily achievable using this technique. This allows surface quality assessments to be made of large solar collecting devices with a precision that is difficult to achieve with other methods.

Introduction

The development of large-scale solar concentrators, such as the 400 m² “Big Dish” developed at the ANU, brings accompanying problems in assessing the quality (i.e., nearness of fit to a perfect parabolic/paraboloidal shape) of their surfaces. A number of methods have been proposed and used to perform these assessments by various research efforts. These have often been accomplished by direct measurement using accurate coordinate displacement transducers connected to a probe. The probe is placed at various positions on the surface to be characterized and coordinates read off the transducers. Other systems have used a scanning laser beam reflected off the concentrator surface and sensed by a detector that can determine the spatial position of the reflected beam (usually) on a plane, and from this surface displacements can be calculated (Wendelin et al., 1991). Another technique has optically assessed the image reflected by a concentrator with a specially marked and/or colored object placed at its focus or radius of curvature (Grossman, 1994). Moiré fringe effect techniques and laser interferometry (Sainov, 1993; Kowarschik et al., 1993; Nadeborn et al., 1993) have also been investigated for surface contour measurement, and provide interesting insights into current endeavors in surface remote sensing (although to the authors’ knowledge have not been implemented for large-scale solar collector analysis).

These methods are mostly applicable to smaller scale collectors (<10 m maximum dimension) and it can be difficult to ensure that both optimum and reliable precisions are achieved in the results. They are also usually system specific, in that they are constructed to assess one particular collector size or geometry, and must be modified and/or reconstructed to assess new collector designs or shapes.

Experiments at the ANU have investigated the usefulness of close range (sometimes referred to as analytical) photogrammetry in the pursuit of surface quality assessments of paraboloidal dish concentrators, with a particular view to determine the actual shape of the recently completed 400 m² (22.6 m effective diameter) “Big Dish,” and from this data to perform a ray trace analysis to predict the flux distribution that will occur in the focal region of this concentrator.

Contributed by the Solar Energy Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS for publication in the ASME JOURNAL OF SOLAR ENERGY ENGINEERING. Manuscript received by the ASME Solar Energy Division, May 1995; final revision, Feb. 1996. Associate Technical Editor: J. H. Davidson.

Photogrammetry: An Overview

Photogrammetry is essentially the science of quantitative analysis of measurements from photographs. Photogrammetry predates photography, as da Vinci and Desargues developed the principles of perspective and projective geometry in the 14th and 16th centuries. The first actual applications of photogrammetry for qualitative mapping occurred with the early photographic processes, but production line mapping systems were not introduced until the 1930s (Slama, 1980).

The most familiar aspects of modern day photogrammetry are maps and charts of the Earth. Aerial photography and photogrammetric analysis are used to produce the vast majority of topographic maps, street directories, and tourist maps in use today. Most of these maps and charts can be described as medium (1:5,000 to 1:50,000) or small scale (1:100,000 and smaller). Smaller scale maps, for example those used in an atlas, are generally derived from compilations of photogrammetric products. All such maps and charts are cartographically designed, analyzed, and enhanced to aid in the presentation of spatial features, and the relationships between features, to the map user.

Photogrammetry is also in use for archaeological and architectural recording, biological measurement, industrial metrology, and engineering surveillance, to name just a few of the many “close-range” applications (Karara, 1989). In many cases a large-scale map or a chart is the result of the photogrammetric measurement, for example a line plot and sections of a building facade undergoing restoration produced for analysis and interpretation by an architect. However, for industrial and engineering applications of close-range photogrammetry, the output of the process is often only coordinates of signalized points on the object. Individual locations to be measured are marked with a target or other unambiguous signal to uniquely identify the point and enhance the accuracy of measurement. Such points may be placed to identify key dimensions of the object, to characterize a surface at a known sampling density. The coordinate set is then subjected to post-analysis, generally by the client for whom the measurement task was undertaken.

Photogrammetry has been used specifically for the recording of various types of antennae. Microwave astronomical (Fraser, 1986) and compact range radar (Fraser, 1992) antennae have been the type most frequently measured by photogrammetry, particularly because of the very high accuracies required to meet the surface tolerance specifications. Photogrammetric measurement of optical reflector systems is less common, al-
though the technique has been used during the construction phase to accurately align the support structures (Gustafson, 1990; Shortis, 1983).

Image Recording and Measurement

Traditionally, images of the object to be measured are exposed from two or more different view points and recorded on film or glass plate negatives. The image locations are then measured using manual or semi-automated devices such as photogrammetric comparators or stereoplotters. A comparator is effectively a very precise x-y digitizer with the facility to record the measured locations in computer readable form. Stereoplotters are typically analogue devices which use an opto-mechanical system to view and measure image locations on the photographs.

The image locations are connected to the corresponding points on the object under the assumption that the camera lens provides a perfect central projection and the focal plane of the camera is perfectly flat. In other words, the image point, the perspective center, and the object point should be collinear (Fig. 1). As no lens system is perfect, either small errors in the otherwise ideal central projection have to be accepted, or models of variations such as lens distortions and image plane unflatness are applied to correct the collinearity. Some cameras are specifically designed for photogrammetric measurement to have insignificant departures from a perfect central projection. The camera lens must have minimal distortions and there must be a vacuum or platen system to flatten the film or glass plate against the focal plane. This is typical of the so-called "metric" cameras, used in aerial mapping systems to produce medium and small-scale maps of the earth.

Cameras used for close-range applications are typically "non-metric" or "semi-metric." In general this means that these cameras have significant departures from a perfect central projection. The departures must be modeled in a calibration process so that the error on the collinearity model can be compensated. The calibration process is beyond the scope of this paper, but can be characterized as a procedure of taking multiple photographs of a test object. If the test object is also the object to be measured, then the process is known as "self-calibration."

The object photographed is then recreated in three dimensions using the principle of collinearity. The observer, combined with the mathematical algorithm, can be considered to be a three-dimensional digitizer which can locate any point which is visible on the surface of the object. Natural and man-made features can be located or delineated to produce regular or free-form descriptors of the surface, limited only by the image resolution. After some post-measurement analysis and processing, simple paper plots or complex CAD/CAM models can be generated from the image measurements in order to visualize the shape of the object, the surface detail, of the object or both.

Photogrammetric Technique

The current investigations have been applied to the following surfaces:

(a) a 5-m diameter paraboloidal concentrator with a circular aperture and 1.8 m nominal focal length, covered with approximately 2400 square, flat mirror tiles, approximately 10 cm on a side;

(b) an approximately equilateral triangular mirror panel, 3.5 m on a side, covered with square mirror tiles 30 cm on a side, with their surfaces curved to produce a paraboloidal shape with a 13.2 m focal length;

(c) one 30 cm on a side curved mirror tile of the type used to cover the surface of the panel described in (b) above;

(d) the 400 m² dish. This has a hexagonal aperture 24.8 m across the vertices and is comprised of 54 triangular mirror panels, of the type described in (b) above, mounted on a space-truss structure such that they form a continuous paraboloidal surface. Each panel has either 30 cm or 60 cm square, curved tiles covering its surface.

In each case a suitable photogrammetric network was adopted based on recognized principles of network design (Shortis and Hall, 1989) to establish the relationship between the camera exposure stations and the points to be measured. In all four cases the essence of the design was to have suitable number of camera stations opposite the rim of the dish or segment, all at the appropriate stand off distance to nearly fill the camera frame with the object (Fig. 2). At each camera station the subject would be centered at the field of view, which requires the camera to be pointed near to the centre of the dish. The central convergence angle in each case was 50-60 deg, which is somewhat less than the 90 deg convergence normally adopted (Frazier, 1986). In these cases the use of manual observations forced the lesser central convergence angle to avoid the exaggerated perspective distortion which is a consequence of the larger convergence angle.

The number of camera stations, and number of photographs at each camera station, is a function of the desired precision of measurement, which in turn is determined by the desired surface tolerance. The minimum number of camera stations is four due to the requirement for a minimum level of reliability, which is formally defined as the ability to detect errors in the image measurements. Additional camera stations improve the reliabil-
ity of the surface measurements, but the number of stations is often limited by the physical environment of the object. Further, camera stations are often chosen for practical reasons, and in the case of the 400-m² dish, six stations were chosen near the vertices of the segment boundaries to make the positioning of the camera relatively simple (Fig. 3). In addition, four exposures were taken at each camera station, though not all were used, to enhance the precision of surface characterization. Additional photographs at each camera station improve the precision in proportion to the square root of the number of photographs. Although the addition of extra photographs realizes a lesser gain in reliability, it is a useful strategy if the number of camera stations is limited by design or practicality.

In all cases the photogrammetric networks were designed to incorporate self-calibration, as a Hasselblad 500/M, 70 mm semimetric camera was to be used. The basic network design was augmented by "rolling" the camera about its optical axis, by 90 deg, to a new orientation at each camera station (Fig. 2). For the largest dish the camera was rolled to four different orientations at every camera station (Fig. 3). The requirement to roll the camera is required to eliminate a phenomenon known as "projective coupling," where certain calibration parameters can become very highly correlated with the positions of the camera stations (Shortis and Hall, 1989).

The photography for the first three surfaces was carried out relatively quickly, as in most cases the camera was hand held. For the 400 m² dish a crane had to be used to position the camera and the photography required a few hours to complete. The thermal expansion of the structure is a complex problem because of the composite materials involved; however, the mild steel frame would expand by approximately 0.3 mm per °C across the 25 m diameter. Although this issue requires further investigation, for this study the temperature of the structure was reasonably stable and therefore the level of movement could be expected to be below the threshold of detection by the photogrammetric measurement.

For positive identification of points on each surface to be characterized, targets consisting of intersecting black and white triangles (inset shown top right in Fig. 4) were fastened in strategic positions over the surfaces to be measured. The 5 m dish had 320 targets placed at the corners of tiles in an essentially random layout (Fig. 3). The triangular panel had 164 targets placed across the surface, with one target being placed at each common intersection of the tile corners. The mirror tile, chosen near the centre of the triangular panel, had 36 targets placed across the surface in a pseudo-regular grid. Lastly, the 400 m² had targets placed near the vertices of each triangular panel, leading to a total of 162 signalized points. The target layout was identical on each triangular panel within the 400 m² dish.

The Hasselblad camera had been previously retrofitted with a reseau plate at the focal plane. The reseau plate contains 27 finely engraved crosses which are imaged onto every negative by masking. Subsequent measurement of the reseau crosses allows compensation for film deformations and unflatness, both of which contribute to departures from collinearity. Kodak "Techpan" black and white negative film was used for all photography due to the stability of the film base and the high resolution of the emulsion. During each set of photographs at least one calibrated distance between two targets was measured to obtain an accurate scale for the object.

Once the photographs were developed, the relative positions of the reseau crosses and observed targets were digitised using an Adam MPS2 analytical stereoplotter (Elfick, 1986). The MPS2 is designed for standard mapping applications using small format stereo photographs, but in this case the instrument was used in a monoscopic mode where one photograph at a time is measured. The digitized reseau cross positions were used to model the film deformations and unflatness in order to correct the positions of the dish targets, now known as image coordinates. These image coordinates, the approximate locations of the camera stations, the approximate orientations of the cameras, the approximate locations of the targets and a nominal calibration for the camera were then processed in a self-calibrating photogrammetric network adjustment for each of the four objects (Shortis, 1993).

In most cases the processing of these network adjustments was fraught with difficulty due to misidentifications of target images. The adjustment is a process of reconciling many hundreds, or perhaps thousands, of observables within a very large parameter space. Any observable or parameter which is not a reasonable approximation of its most probably true value tends to influence all parameters and the network solution will oscillate or fail completely (the calculation is carried out by an iterative least squares estimation solution which is considered successful when the corrections to the parameters fall below a preset threshold level). Many manual observations of many target images on many photographs inevitably leads to human error, and isolation of the misidentifications is a difficult and tedious task carried out essentially by reviewing the data manually. The use of many camera stations would tend to alleviate this problem, as robust estimation techniques could be usefully employed to improve the error detection.
Table 1 Summary of the results of the photogrammetric network adjustments

<table>
<thead>
<tr>
<th>Object</th>
<th>Number of stations</th>
<th>Number of photographs</th>
<th>RMS image residual (μm)</th>
<th>Mean target coordinate precision (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m dish</td>
<td>4</td>
<td>4</td>
<td>7.68</td>
<td>0.9</td>
</tr>
<tr>
<td>Mirror panel</td>
<td>4</td>
<td>4</td>
<td>2.74</td>
<td>0.4</td>
</tr>
<tr>
<td>Mirror tile</td>
<td>4</td>
<td>4</td>
<td>4.14</td>
<td>0.04</td>
</tr>
<tr>
<td>400 m² dish</td>
<td>6</td>
<td>12</td>
<td>1.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Once the major errors were removed, the more minor errors and inconsistencies in the data were deleted automatically using statistical testing. The results of the final network adjustments are the most probably true values of the calibration parameters for the camera, the locations of the camera stations, the orientations of the camera at each station and, most importantly, the three-dimensional coordinate values defining the positions of each of the targets in space. Also available from the network adjustments are the residual errors in the image measurements and the estimated precisions of all parameters and coordinates.

Table 1 presents a summary of the results for each object measured. It is clear that although there are some inconsistencies due to the various scales of the photography and the consequent size of the target images, the root mean square (RMS) image coordinate residual is reasonably uniform. Further, the target coordinate precision is essentially proportional to the size of the object, improved by the extra photographs in the case of the 400 m² dish. Although 24 photographs were taken for this dish, only 12 were observed and processed in the network adjustment. The most time-consuming part of the process is the manual observation of the target images on the photographs, and extra photographs could have been observed if the improvement in precision was warranted.

The adjustments were conducted in “free network” mode, which essentially means that there were no external constraints of any kind on the photogrammetric data. The only external data required is a minimum of one, accurately known, straight line distance between specified points on the surface to be measured. This is mandatory to provide an accurate overall scale of the object, if necessary. A consequence of this is that there is no object space “control” and the target coordinate results are produced with an arbitrary orientation. These were adjusted such that the surfaces took up their expected spatial orientation by use of a three-dimensional similarity transformation to the appropriate datum plane in each case. Figures 5 through to 8 show the photogrammetrically determined surfaces for the 5 m dish, the triangular mirror panel, the mirror tile and the 400 m² dish, respectively.

The proportional accuracies for the characterization of the surfaces range from 1:5,500 to 1:19,000. The most favourable result is for the 400 m² dish, as this measurement incorporated more camera stations and more photographs than the smaller surfaces. Further gains in proportional accuracy could be made by alterations to the geometry of the camera stations and, in particular, further additions of stations and photographs. However, the gains in accuracy would be at a considerable cost. Although the measurement process on the MPS2 is semi-automated, the fine positioning for target observations must be made by the operator, so additional images demand a commensurate increase in observing time.

Conclusions

Economies of scale are still being investigated to determine the optimum, most cost-effective size for solar concentrator installations. As larger collectors are built for assessment purposes, photogrammetry offers an accessible tool for simplifying the difficult job of surface characterisation of these, and other solar collecting structures. The above results indicate that photogrammetry does have the capability to determine surface coordinates within an accuracy suitable for the assessment of most solar concentrators.

Photogrammetry has a number of advantages as a general measurement system. First, it is a noncontact remote sensing technique and the only direct information required is a single distance to scale the object accurately. The approximate camera station locations, target coordinates, and a nominal camera calibration must also be known, but these can be estimated after...
the photography. Photogrammetry can assess surfaces of almost any size or orientation and the same equipment can be used to characterise any surface. The precision of the surface characterization can be varied by varying the geometry of the network, in particular the number of camera stations and photographs. Lastly, photographic records can be kept in archival storage for remeasurement if reassessments are required or for additional photographs to be observed as needed.

Like all measurement tools, photogrammetry also has its disadvantages. The capital cost of equipment, and/or the cost for commercial film-based photogrammetric assessment, is relatively high. For example, a system comprising the Adam MPS2 and the Hasselblad with the retro-fitted reseau plate would cost of the order of 50,000 AUD. Although photogrammetric techniques are well documented in the literature and equipment can be purchased "off the shelf," the novice user faces a steep learning curve. Comprehensive knowledge of photogrammetric systems, measurement processes, computational algorithms, and results analysis is a very specialized expertise which can only be gained from a combination of training in optical metrology and experience with project work. The technique is limited by the quality and resolution of the photography, and photogrammetry can be impractical in situations where very convoluted surfaces are to be measured or where there are many foreground obstructions. Also, in the cases of reflective or featureless surfaces, attaching targets to the surface is mandatory. Finally, it should be noted that the technique does not provide surface normal information directly, although this can be determined mathematically from a fitted surface through the measured data points.

However, perhaps the most pressing problem for film-based photogrammetry is that the observation of the target images is labor-intensive and therefore costly in terms of time and resources. Automation of this process has been the subject of research during the last several years and digital image based systems are only now becoming widespread. Digital systems use either conventional film which is then scanned (Shortis, 1988) or a still video-type camera is used to capture the digital image directly (Fraser and Shortis, 1995). A number of commercial systems, based on still video cameras and portable computers, have become available in recent years, servicing primarily the aerospace and manufacturing industries (Beyer, 1995). Although such systems can still have limitations imposed by the expertise of the user, the resolution of the CCD sensors and the large storage requirements of digital images, the prospects for automated systems is extremely promising.

Acknowledgments

The author (GJ) would like to thank Prof. Peter Morgan (University of Canberra) for his assistance with the use of the Adam MPS2 and Hasselblad camera, Dr. Mike Elfick (University of Suneying and Land Information, University of Melbourne, Australia) for his advice and generous help, and the staff at the Energy Research Centre (ANU) for their advice, discussions, and technical support. Many thanks are also due to the Northern Territory Power and Water Authority, Pacific Power, New South Wales Office of Energy, ANUTECH, the Energy Research and Development Corp., Electrical Distribution and Transmission of South Australia, Queensland Electricity Commission and the State Electricity Commission of Victoria for their financial support of the research undertaken in this paper.

References