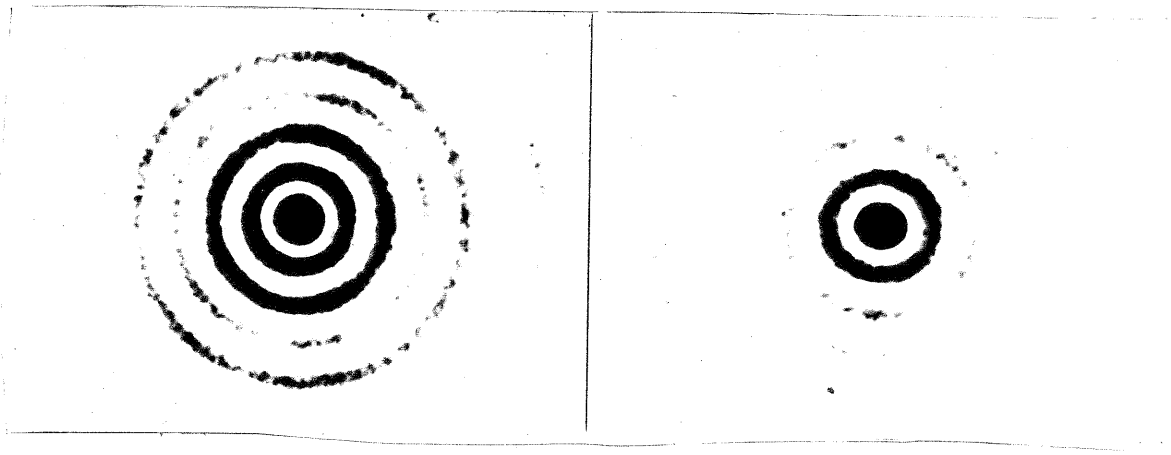
# Progress with the NPL Centrax Camera System

by J M Burch and C Forno
DMOM, NPL Teddington, England

## Introduction

The NPL Centrax camera has been designed for ultra-precise work in close range photogrammetry. For this type of application it is seldom satisfactory to rely on natural object features, such as surface texture or edges, and in most cases specially designed targets are used to define the points being studied. If these targets are made small, symmetric and self-luminous, then it becomes a useful alternative to dispense with conventional photographic imaging and to redesign the lens so that the images which it produces, although larger than usual, have their positions sharply defined by a central diffraction pattern. These central patterns are referred to as "axicon images"; each of them contains a small bright spot surrounded by several concentric diffraction rings of almost regular spacing and gradually decaying intensity (Figure 1).



(a) on-axis

(b) off-axis

Figure 1. Axicon images recorded by the Centrax with white light

A second important feature of the Centrax lens is that it is designed to be monocentric. The camera is therefore intrinsically free from distortion and its axicon images remain equally sharp and symmetrical for all the bright points in the targeted object-space.

## Centrax Lens

The particular lens configuration that is being investigated at NPL is illustrated in Figure 2. It consists of a central sphere surrounded by two hemi-spherical shells with an opaque periphery.

In the example shown the shells are made of light flint glass and the sphere of borosilicate crown. All three components have been fabricated so that when the lens is assembled, using a cement whose index matches the flint glass, the surfaces will be concentric with each other to within ± 0.2 µm. There is also a requirement for the two outer surfaces to be spherical within 20nm, but apart from this small departures from the dimensions or refractive indices quoted in the constructional data of Table 1 produce only a slight alteration of the camera-object working range.

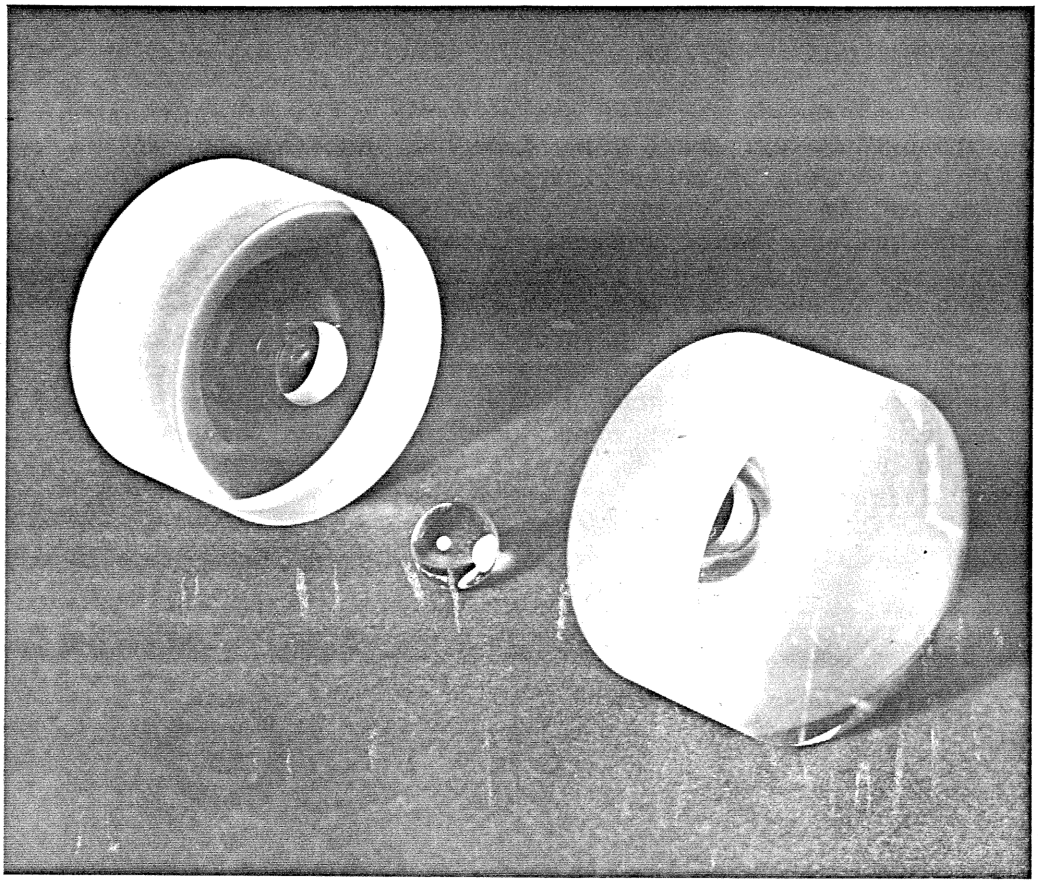


Figure 2. All glass version of the Centrax

| Surface no | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Radius (mm) | 28.6 | 5.0 | -5.0 | -28.6 |

| Refractive index | 1.5485 | 1.5106 | 1.5485 |
|---|---|---|---|

Table 1. Constructional data of the solid Centrax

The final assembly and cementing of the lens has not yet been completed, but a detailed initial investigation of the performance of this design has been made using a liquid-filled prototype of the Centrax (1,2). In this lens the outer shells are of fused silica and the central chamber is filled with a liquid of index 1.426 consisting of a solution of 61.5% glycerol in water. The lens is mounted in a stainless steel camera body with provision to adjust the alignment of the two components. The overall size of the camera, complete with dark-slide, is 135 mm x 100 mm square (Figure 3). In order to avoid any effects of dimensional instability thick glass plates, 75 mm x 75 mm x 5 mm, are used as a substrate for the fine-grain photographic emulsion.

We anticipate some improvement in optical performance from the solid version, by virtue of the perfection of the central sphere. Nevertheless, the liquid-filled Centrax has remained stable and accurately aligned for more than 2 years.

The optical properties of this lens have already been described but the main features are summarized in Table II, Included in this table is a re-evaluation of the effective "f" number which indicates approximate exposure requirements relative to a conventional lens.

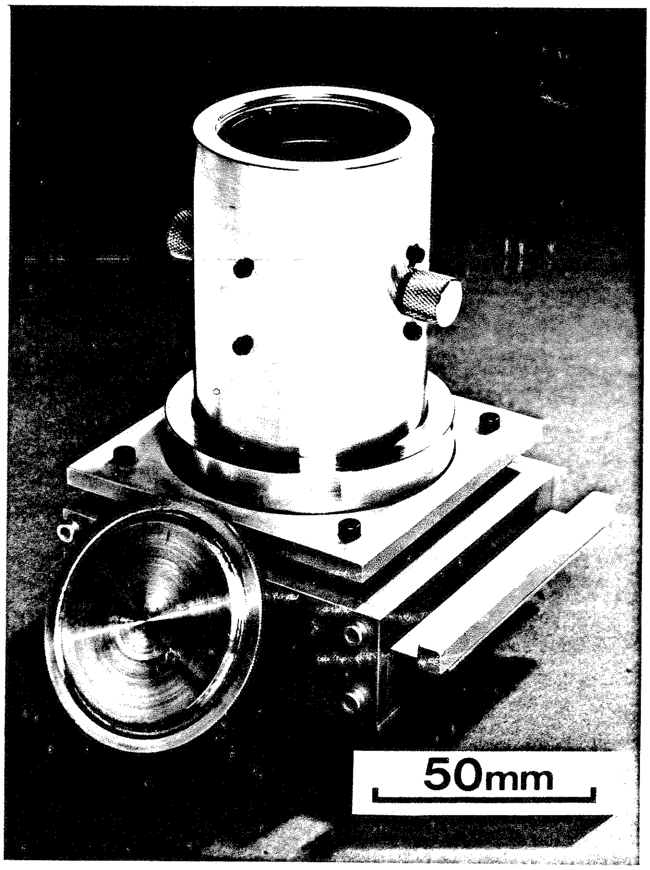


Figure 3. The prototype Centrax camera

| | |
|---|---|
| Principal distance.................. | 71 mm. |
| Field angle.......................... | ±20° |
| Effective f/no....................... | $\bar{f}/25$ |
| Depth-of-field....................... | 300 mm to infinity |
| Mean axicon ring spacing............. | 4 µm |
| Max. target subtense................. | 30 µrads |

Table II. Optical properties of the liquid filled Centrax

## Cooperative Targets

It has already been indicated that the Centrax is used in conjunction with small, self luminous targets. For laboratory studies, or where there is some control over the ambient illumination, the simplest small source target that can be employed in conjunction with the Centrax is a polished steel ball. The ball is illuminated from a position in the vicinity of the camera using a conventional white-light source, such as a quartz iodine lamp. It is essential, however that the reflected image of the source is small enough to ensure that the demagnified axicon image recorded by the Centrax is not blurred by more than one half of the axicon ring spacing, ie 2 µm.

For the present camera, with a principal distance of 71 mm, the approximate maximum diameter of the ball b, is related to the diameter of the source S, the ball-source distance $D_1$ and the ball-camera distance $D_2$ by:

$$b = 10^{-4} (D_1 . D_2/S)$$

Unless the illumination provided for the ball targets concides with the centre of the Centrax lens, there will be some transverse displacement of the reflected image in each ball with respect to the camera-target vector. If the approximate position of the source and of each ball is known then a correction can be calculated for each image shift.

Since the axicon image is diffraction limited its intensity will depend on $D_2^{-2}$, assuming the reflected energy from the ball is constant. The energy reaching the ball from the source, however, is not constant but falls as $D_1^{-2}$. As a result, if the camera and source are close to each other the intensity of the axicon image falls as the inverse fourth power of the distance. In practice this is likely to produce an excessive variation in the density of the processed images generated by object points at different positions, especially when the conventional high-contrast developers are used.

These variations can be compensated partially by using larger balls for the more distant targets, but this approach fails with highly convergent photography. A more general remedy is to modify the development of the photographic plate. A low contrast developer, such as D165 (3) can accommodate variations in relative intensities over a range of at least 16:1 which is equivalent to a 2:1 change in $D_1$ and $D_2$. If the developer is left undisturbed during processing then this also helps to restrict the density of overexposed images because of localised exhaustion of developing agent.

## Facilities for plate measurement

Several tests were made using the camera mounted on a precision Moore 1440 division serrated turntable and these indicated that any distortion that was present did not exceed 60 nm. The tests involved measuring the positions of recorded images along one direction by setting visually through a measuring microscope equipped with a linear interferometer. For photogrammetric studies involving real structures this single interferometer system is inadequate as measurements over a 2-dimensional field are required.

Our first full field investigations have been carried out using a standard ZKM Zeiss measuring microscope which allows an absolute positional accuracy of approximately ± 0.5 µm in x and y. In order to exploit the camera potential, however, an improvement in accuracy of an order of magnitude is necessary. Currently a similar microscope is being modified with two Hewlett Packard interferometer fringe counting systems, measuring from the polished surfaces of a square fused silica ring that is mounted on the stage so as to enclose the plate.

As an attachment for use with this microscope a photoelectric sensor system has been built which will scan a focused laser beam in a small circle round the central black spot of each axicon image. Experiments indicate that it will be possible by this means to measure the image coordinates to within 50 nm rms uncertainty.

## Full field test

A preliminary assessment with highly convergent photography has now justified some of our predictions regarding the performance of the Centrax. It involved photographing a stable structure from 4 different stations using a single camera. The structure, assembled on a rigid aluminium alloy casting, consisted of 27 steel pillars, 38 mm x 38 mm across and of three heights: 20 mm, 150 mm and 280 mm. Each pillar was targeted by cementing a 4 mm dia polished steel ball to a depression in the top. The casting was supported kinematically on a heavy-duty rotary table by means of 3 large steel spheres. When viewed obliquely from above, by a single camera, all 27 targets on this "Manhattan" model could be seen for 4 successive positions of the rotary table (Figure 4). In this orientation the camera was approximately 0.8 m from the centre and at 45° to the vertical axis of the table. A small 100 watt QI projector, arranged approximately 240 mm above the camera, provided a shadow-free illumination of each ball and was sufficiently far away to avoid the introduction of convection currents.

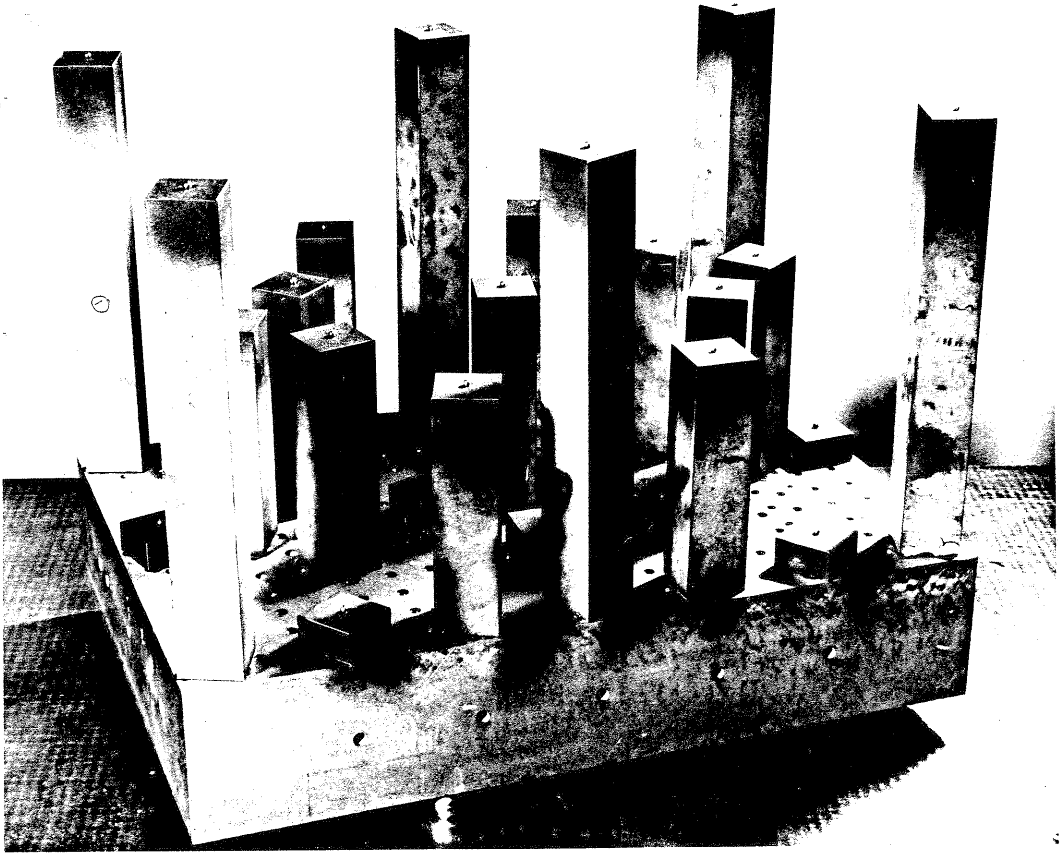


Figure 4. The "Manhattan model"

For convenience, the 4 records were exposed on one plate. This reduced the labour in the measurement of image coordinates and the corrections for plate flatness. Because of the symmetry of the structure, however, the proximity of some of the images caused problems in image identification, especially since all the axicon patterns have a similar appearance. By re-photographing the structure, with an SLR camera in place of the Centrax, this ambiguity was quickly resolved.

The positions of the images on the processed plate were determined by visually setting only once under the ZKM measuring microscope. A measure of the surface flatness, using a Fizeau interferometer, provided individual corrections to the image coordinates of the form:

$$\Delta x = n(x-x_o)/224000$$

where n is the fringe number in the Fizeau pattern, relative to a value 0 at the edge of the field, and $x_o$ is the principal point position (all dimensions in mm and $\lambda$ = 633 nm).

## Analysis of results

Four image positions were measured for each of 27 object points. The uncorrected image coordinates were analysed with a bundle adjustment program developed by Dr R A Hunt. This program, "Grundle", has no self-calibration but includes an adjustment to the principal distance and the position of the principal point. Such adjustments are necessary because of residual uncertainties in location and flatness of the photographic plate. Once the approximate object coordinates have been obtained, ball corrections are calculated and the program is re-run. An assessment of residual uncertainties by this method does not necessarily require knowledge of the absolute coordinates of any control points in the object frame or of camera parameters.

Nevertheless, a comparison between photogrammetrically determined object coordinates and coordinates derived from an accurate mechanical measurement provides additional information on the Centrax performance. Accordingly, following photographic recording, the "Manhattan model" was transported to a Moore 5Z 3-axis measurement facility where the positions of a number of points in the top and central planes were measured precisely. Values for two points were used as an absolute scaling factor in the "Grundle" program and one ordinate value for a third point was used as a loose constraint in the orientation of the structure. At this stage the rms residual on image coordinates was approximately 0.5 µm. Fizeau corrections for localised errors of plate flatness were inserted but this did not significantly reduce the residual uncertainties. It seems likely that the ZKM is the dominant source of error.

The residual uncertainties refer to plate coordinates and the figures in brackets alongside the object coordinates indicate the departures in micrometres from target positions measured on the Moore 5Z. Although the comparison between 3 points only is not statistically significant, the differences reflect not only inaccuracy from the photogrammetry but also actual dimensional changes that may have occurred during transport as well as uncertainties of the order of 1 or 2 micrometres in the Moore 5Z. A calculation of the rms values of the residual uncertainties for both x and y shows that the y error rms value, at 0.5 µm, is greater than for x at 0.4 µm. It has indeed been found that for the particular microscope used the greater error exists in the y-measurement direction.

| Object coordinates | | | Plate residual uncertainties | | | |
|---|---|---|---|---|---|---|
| X | Y | Z | 1 | 2 | 3 | 4 |
| -226.648 | 127.161 | 147.907 | 0.0014 | 0.0006 | 0.0009 | 0.0010 |
| -224.286 | -133.207 | -1.793 | 0.0010 | 0.0009 | 0.0009 | 0.0008 |
| -225.162 | 127.138 | -151.636 | 0.0009 | 0.0014 | 0.0015 | 0.0004 |
| -148.204 | -132.515 | -151.271 | 0.0002 | 0.0006 | 0.0003 | 0.0007 |
| -175.191(0) | -2.748(0) | -1.652(1) | 0.0003 | 0.0009 | 0.0004 | 0.0005 |
| -149.365 | -132.661 | 148.592 | 0.0010 | 0.0007 | 0.0005 | 0.0012 |
| -123.552 | -2.265 | 48.426 | 0.0007 | 0.0003 | 0.0006 | 0.0004 |
| -124.934 | -2.309 | -51.320 | 0.0006 | 0.0004 | 0.0003 | 0.0005 |
| -74.075 | -1.888 | -151.823 | 0.0003 | 0.0005 | 0.0004 | 0.0001 |
| -49.123 | -131.820 | -0.520 | 0.0002 | 0.0008 | 0.0007 | 0.0002 |
| -76.397 | -2.014 | 148.826 | 0.0004 | 0.0000 | 0.0004 | 0.0005 |
| 0.748 | 128.887 | 149.502 | 0.0006 | 0.0002 | 0.0005 | 0.0004 |
| 0.759 | -131.439 | 73.994 | 0.0005 | 0.0003 | 0.0004 | 0.0002 |
| -0.003(2) | -1.417(4) | -0.667(4) | 0.0008 | 0.0003 | 0.0007 | 0.0002 |
| 1.530 | -131.399 | -75.465 | 0.0000 | 0.0007 | 0.0007 | 0.0005 |
| -3.454 | 129.071 | -149.594 | 0.0004 | 0.0008 | 0.0007 | 0.0004 |
| 77.174 | -0.509 | -150.504 | 0.0004 | 0.0006 | 0.0008 | 0.0002 |
| 50.914 | -130.968 | -0.399 | 0.0005 | 0.0004 | 0.0005 | 0.0003 |
| 73.949 | -0.718 | 149.711 | 0.0005 | 0.0014 | 0.0012 | 0.0009 |
| 124.499 | -0.463 | 50.520 | 0.0006 | 0.0005 | 0.0007 | 0.0006 |
| 126.641 | -0.349 | -50.190 | 0.0004 | 0.0004 | 0.0004 | 0.0003 |
| 152.067 | -130.163 | -149.881 | 0.0006 | 0.0005 | 0.0002 | 0.0007 |
| 174.999(1) | -0.008(8) | -0.004(4) | 0.0006 | 0.0002 | 0.0002 | 0.0003 |
| 150.119 | -130.267 | 150.357 | 0.0010 | 0.0004 | 0.0012 | 0.0005 |
| 222.621 | 130.605 | 150.132 | 0.0007 | 0.0004 | 0.0008 | 0.0009 |
| 226.229 | -129.537 | 0.760 | 0.0011 | 0.0005 | 0.0003 | 0.0008 |
| 224.878 | 130.595 | -149.083 | 0.0004 | 0.0006 | 0.0005 | 0.0005 |

Table III. Results from the "Manhattan model" study

Attempts have been made to expand the interpretation of the data, for example by compensation of the microscope drift which occurred during measurement. Little improvement was found and it would seem that we have reached a limit set by residual systematic error.

As soon as the interferometric ZKM becomes available measurement of the plate coordinates will be repeated and this should provide a clearer indication of the residual errors of the Centrax camera. Meanwhile, however, these first results from the "Manhattan model," together with the earlier study of radial distortion, are encouraging. With a convergent system of 3 Centrax cameras, mounted on a rigid triangular frame and used in conjunction with the modified ZKM microscope, a precision of 1 μm per metre may ultimately come within reach.

The authors acknowledge the care and dedication with which colleagues in the NPL Glass Workshop have successfully fabricated the first examples of these lenses. We also thank Mr A B Penfold and Mr P J Collins for building the axicon image sensing unit.

## References

(1) J.M. Burch and C. Forno. Proc SPIE Vol 399 "Optical System Design, Analysis, and Production". Geneva, 412-417, 1983.

(2) J.M.Burch and C.Forno., Proc ISPRS Commision V "Precision and Speed in Close Range Photogrammetry", 90-99, 1982.

(3) D165 developer. Metol 1.5g, Sodium Sulphite 6.3g, Sodium carbonate 9g, Potassium bromide 0.2g, water to 1l (solution will not keep).