1992PASAU..10...74C

Redesigning a Baker-Nunn Camera for CCD Imaging

B. D. Carter, M. C. B. Ashley, Y-S. Sun, and J. W. V. Storey, *School of Physics, University of New South Wales, Kensington NSW 2033*

Abstract: The University of NSW's Automated Patrol Telescope is a modified Baker-Nunn satellite tracking camera, now used for CCD imaging of astronomical objects. The f/1 Baker-Nunn optical design gives a 30° field of view with an approximately spherical focal surface of radius ≈500 mm. While the focal plane curvature is tolerable across the 1.4° × 1.0° field of the present CCD, it becomes unacceptable when a larger CCD is used. In addition, the use of glass filters in the highly convergent beam produces intolerable spherical aberration. We present a design modification to the original Baker-Nunn which enables a 5° diameter flat field to be produced when using B, V, R or I filters. By making this modification, we plan to perform multicolour imaging, using a new large-format CCD with a 2.9° × 1.9° field of view.

1. Introduction

The School of Physics, University of NSW, has recently converted a Baker-Nunn satellite tracking camera into an Automated Patrol Telescope (APT) for astronomical research. The Baker-Nunn camera is one of several manufactured in the United States in 1957, and our particular camera was originally used at Woomera for tracking artificial satellites. In 1982 the instrument was donated to the UNSW by the owner, the Smithsonian Astrophysical Observatory. The mount of the instrument was converted to equatorial, the drive system was changed, and a CCD replaced the film holder used for satellite-tracking work. Telescope slewing, guiding and data acquisition were placed under computer control to facilitate automated searches and monitoring observations (Cochrane *et al.* 1985). The APT has been in use performing CCD imaging since its opening in June 1989, taking images for the astronomical research of PhD students in the School of Physics (Payne 1992, Brooks 1990, 1992). A new Peltier-cooled CCD camera is currently being completed (Carter and Ashley 1991) and an automatic cloud monitoring device is being installed (Ashley and Jurcevic 1991).

2. Motivation for Modification of the Optics

(a) The Baker-Nunn optical system

For its original purpose of tracking earth satellites, the most important function of the camera was to provide an exceptionally wide field of view, and to be able to record faint satellites. To do this, large-format 55 mm Cinemascope film was used, and the optics were designed to produce point source images of size comparable to the film resolution. The original specifications for the optics were to put 80% of the light within a 20μ diameter blur circle, over the 5° × 12° field of the film. Moreover, a fast (f/1) system was required, and these optics were expected to produce fully colour-corrected images across the entire visual spectrum.

Such demanding imaging criteria resulted in a modified Schmidt design with a 3-element correcting lens. The clear aperture of the instrument was 0.5m and the focal ratio f/1, making the telescope an excellent wide-field camera for astronomical survey work for stellar and extended objects. The Baker-Nunn design exceeded the above criterion for a wide field, and produced sharp images over a 30° field of view. This remarkable design work was performed by Dr James Baker in an early use of electronic calculation applied to optical ray-tracing. The detailed specification of the optical system, and additional information, was kindly supplied to us by the designer (Baker 1991, see also Baker 1962, Dunn 1969).

Table 1. The original Baker-Nunn design

Surface	Curvature mm^{-1}	Separation mm	Aspheric coefficients A4	A6
1	−0.000072738	0	0	0
2	−0.00038734	26.78	−1.297E−9	+1.633E−15
3	−0.00033593	47.60	−1.477E−9	+7.369E−16
4	+0.00033583	19.54	+1.477E−9	−7.369E−16
5	+0.00038653	47.52	+1.297E−9	−1.633E−15
6	+0.000072902	27.02	0	0
7	−0.00098409	944.80	0	0
8	−0.0019685	−520.65	+2.156E−10	0

We measured the shape of the lens elements both mechanically and optically. A micrometer was used to measure the depth of each lens surface below a reference plane, at 8 points along a diameter of the lens, to an accuracy of 0.01 mm. The measurements from several diameters were averaged and a computer program was used to fit radii of curvature and A4 and A6 aspheric coefficients. The radii were also checked optically by using the concave surfaces as mirrors, and by determining the focal length of the central few centimetres of each lens. The mirror radius was measured with a stick-micrometer and a knife-edge. A summary of all the measurements is shown in Table 1 (see Figure 1 for the optical layout). There are small but significant departures from the original specifications, particularly in the separation of the lens surfaces. The radii of curvature, however, are very close to the specifications, for example, the mirror was measured as 1016.17 ± 0.10 mm and was specified as 1016.23 mm. We were unable to measure A4 and A6 to better than 2% accuracy, at which point they agreed with the specifications, so we have used the specified values in what follows.

The outer two surfaces of the corrector are spherical, the inner four surfaces are matched pairs of aspherics. The outer elements of the corrector are made from KzFS-2, whereas the centre element is SK-14; the refractive indices for the glasses are shown in Table 2. Since film can be curved to fit

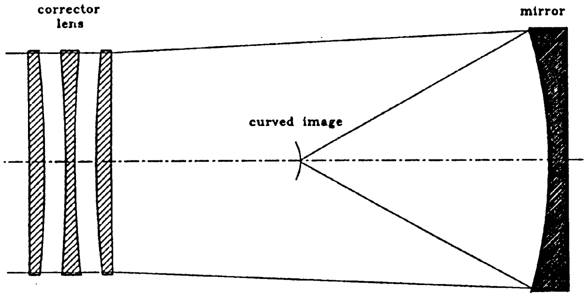

Figure 1 — The original Baker-Nunn design, producing a curved focal surface.

Table 2. Refractive index data

Glass	486.1 nm	546.1 nm	587.6 nm	656.3 nm
KzFS-2	1.565479	1.560767	1.55831	1.555150
SK-14	1.609992	1.605452	1.60308	1.600046

the focal surface, the excellent performance of the Baker-Nunn optical design is achieved in part by allowing the focal surface to be curved. The focal surface is almost spherical, with a radius of curvature of $\approx$500 mm.

(b) Adapting the optics for a large CCD

Optical aberrations arise when images from the telescope are recorded with a large, flat CCD instead of photographic film, or a filter is used in the beam.

For the CCD presently in the APT (an EEV P8603 chip of 578 × 385 pixels each 22μm square), curvature of the focal plane is negligible over the 1.4° × 1.0° field. However, to enhance the capabilities of the APT we will be installing a larger CCD, coated in order to improve its response to the blue end of the visual spectrum. The new CCD is four times the area of the present CCD, and a curved focal surface would produce unacceptable blurring towards the edges of the chip.

In addition to the new CCD, we plan to use a set of B, V, R and I filters, each 5 mm thick, to perform precise photometry with the telescope. However, this extra glass placed in the telescope's highly convergent f/1 beam results in severe spherical aberration, spreading stellar images over several pixels.

Moisture damage to the outermost surface of the lens was another important factor in our decision to rework the optics. To achieve the necessary optical specifications, Baker used special soft glass of low refractive index in the two outer elements of the corrector triplet lens. These lens elements are mildly hygroscopic and deteriorate through exposure to the atmosphere. Over the years the first lens surface has become affected, giving the surface a milky, translucent quality, and causing loss of throughput and contrast. We were therefore committed to repolishing the first surface, and decided to investigate possible changes to its shape that might improve the performance of the telescope for our application.

3. Specifications for the Revised Optical System

Using detailed optical specifications for the camera, we performed ray-tracing of the system on a computer, to characterise the existing optical design, and test the effect on star images when a CCD and filter were installed. We then experimented with a number of changes or additions to the optical elements, and optimised the new design to minimise spherical and chromatic aberration, and curvature of field, while keeping constant as many as possible of the telescope's parameters in order to reduce costs. The software we used was the program available from Kidger Optics Ltd of the U.K., and was run on an IBM-PC compatible computer.

The size of our new large format CCD gives a 2.9° × 1.9° field. This chip, manufactured by EEV, has 1152 × 770 pixels, each 22.5μ across, equivalent to 9 arcseconds on the sky. To accommodate this CCD, and future, larger CCDs, we worked to a specification of a 5° diameter field with ~ 20 μm images in the presence of a 5 mm filter placed immediately in front of the CCD.

By making the light from a star fall within one pixel, we optimised the design to detect the faintest objects by minimising the sky background recorded. Hence, the signal to noise ratio of an individual measurement is optimum for faint object detection, and will thus produce the best photometric accuracy possible for a given magnitude star. Although 1-pixel images leads to severe undersampling, we expect aperture photometry will require a grid of 3 × 3 pixels to ensure an image is properly recorded when the image centroid is randomly placed within the confines of a given pixel.

Several alternative approaches to the optical design were examined. The alternatives included refiguring the primary mirror, respacing the three corrector elements, and adding a fourth corrector element (which would double as a weather shield). While some of these approaches did produce satisfactory images, none of them offered the overall performance and simplicity of the design finally chosen.

The final design, which is the result of extensive ray-tracing experiments, produces excellent images without requiring re-spacing of the corrector lens elements or changes to any but the first optical surface. The required changes were:

(a) modify the first surface of the optical system from a spherical to an aspheric shape,

(b) move the primary mirror about 6 mm closer to the corrector, and

(c) add a bi-convex field flattening lens, which doubles as the window of the CCD vacuum housing.

(d) coat the first surface with a MgF$_2$ layer to protect it against further water damage.

The new layout is in Figure 2, and the specifications are given in Table 3.

4. Imaging Performance Results

The ray-tracing analysis shows that the image quality of the original Baker-Nunn, according to the actual measured specifications, is inferior to Baker's slightly different design specification. Our Baker-Nunn in its original form produces a maximum spot size one-third larger than that predicted by the design Baker developed (Dunn 1969). However, even Baker's exact design does not produce the large flat field we require for CCD imaging.

The new, modified optical system produces images half the size of the original Baker-Nunn, through the V filter, the filter for which we optimised the design. The results are also

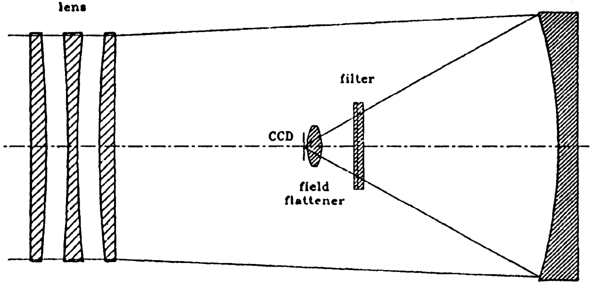

Figure 2 — The modified Baker-Nunn design, which produces a flat focal plane suitable for CCD imaging.

Table 3. The modified Baker-Nunn design

Angle from field centre	Original design Curved field	Flat field	Modified design B	V	R	I
0°	40	40	35	15	30	40
1°	40	100	35	15	30	40
1.7°	40	unusable	30	10	25	35
2.5°	40	unusable	20	15	20	35

Table 4. Spot sizes (μm) for the original and modified Baker-Nunn designs

Surface	Curvature mm^{-1}	Separation mm	Aspheric coefficients A4	A6
1	−0.000052632	0	+1.932E−11	+1.462E−16
2	−0.00038734	26.78	−1.297E−9	+1.633E−15
3	−0.00033593	47.60	−1.477E−9	+7.369E−16
4	+0.00033583	19.54	+1.477E−9	−7.369E−16
5	+0.00038653	47.52	+1.297E−9	−1.633E−15
6	+0.000072902	27.02	0	0
7	−0.00098409	934.00	0	0
8	0	−493.72	0	0
9	0	−2.00	0	0
10	0	−3.00	0	0
11	−0.0056180	−16.78	0	0
12	0	−4.00	0	0
13	0	−1.56	0	0

satisfactory for the B, R and I filters. The performance of the new design is summarised in Table 4, where the calculated maximum spot size as a function of distance from the optical axis is listed, both for the original, measured optical system, and for the new design with various filters. For the new design, point source images up to 2.5° from the optical axis are ~ 20μm throughout the original visual wavelength range for which the Baker-Nunn was designed (B, V, and R). I-band imaging performance appears poorer, although we cannot accurately predict it since we only have approximate I-band refractive index data for the glasses.

5. Conclusion

The new design provides a flat 5° field of view, for future larger CCDs or CCD mosaics. The sharper point source images in the V filter, compared to the original Baker-Nunn, may also enhance the use of CCDs with smaller pixel sizes.

In conclusion, the Baker-Nunn optics can provide excellent wide-field CCD imaging performance in the standard photometric bands, after relatively straightforward modifications. The modifications will be carried out over the next few months, and the results reported in a subsequent paper.

Ashley, M. C. B. and Jurcevic, J. S., 1991, *Proc. Astron. Soc. Aust.*, **9**, 334.

Baker, J. G., 1962, U.S. Patent 3,022,708, which describes the Baker-Nunn design.

Baker, J. G., 1991, private correspondence.

Brooks, P. W., 1990, *Proc. Astron. Soc. Aust.*, **8**, 377.

Brooks, P. W., 1992, PhD thesis in preparation.

Carter, B. D. and Ashley, M. C. B., 1991, *Proc. Astron. Soc. Aust.*, **9**, 158.

Cochrane, J. W., Mitchell, P., Payne, P. W., Storey, J. W. V. and Webster, B. L., 1985, *Instrumentation and Research Programmes for Small Telescopes*, IAU Symp. 118, J. B. Hearnshaw and P. L. Cottrell (eds), D. Reidel.

Dunn, J. M., 1969, Perkin-Elmer Engineering Report No. 9709, Perkin-Elmer Corporation, Optical Group, Norwalk, Connecticut.

Payne, P. W., 1992, PhD thesis in preparation.