Development of ARIES Baker-Nunn camera to a wide-field Imaging Telescope with CCD

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Abstract. ARIES Baker-Nunn Schmidt telescope project is converting a Baker-Nunn satellite tracking camera for Astronomical research. Original Baker-Nunn camera produces an extremely large ($5\times30$ degree) curved focal plane at the prime focus for photographic imaging. We present here the re-designing of the camera produces a wide ($4\times4$ degree) flat field of view for CCD imaging observations, which have many scientific potentials in Astronomy. Imaging performance of the CCD camera is also estimated.

1 Introduction

The ARIES Baker-Nunn Schmidt telescope project was initiated during 2005 to use its wide-area imaging capabilities for numerous scientific purposes with modern CCD detector. The telescope will be installed at Manora Peak, Nainital, India (longitude: 79° 18′ 00″ E and latitude: 29° 22′ 00″ N).

Scientific programs like study of variable stars, Asteroids and Near-Earth-Objects, detecting of extra-solar planets though transit method, transient objects like GRBs and supernovae, and imaging of large star clusters could be suitably accomplished with this wide-field imaging telescope. The photographic Palomar all-sky surveys is one of most important contribution from the 1.2-m Samuel Oschin Schmidt, 1.2m UK-Schmidt and 1-m ESO Schmidt telescopes [1]. The Near-Earth Asteroid Tracking (NEAT) project has recently instrumented the Palomar Samuel Oschin telescope with 4080 × 4080 CCDs covering of $\sim3.75$ deg² field of view [2]. Recently, QUEST (Quasar Equatorial Survey Team) collaboration [3] uses the 1-m Schmidt telescope located at the Venezuelan National Astronomical Observatory with 16 CCDs (2048 ×2048) arranged in a $4 \times 4$ mosaic covering 2.3° × 3.5° of the sky [3]. The Automated Patrol Telescope (APT) [4] at Siding Spring Observatory, Australia operated by the University of New South Wales (UNSW) uses a 0.5m telescope with 770 × 1150 CCD covering $2° \times 3°$ field of view [4-5]. The UNSW Extra-solar Planet Search is the major

1 http://neat.jpl.nasa.gov/
2 The collaboration includes several US Universities and CIDA (Venezuela)
3 http://www.phys.unsw.edu.au/ mcba/apt/
scientific project using the APT facilities \cite{6}, and produced several variable stars as a byproducts \cite{7,8}. The Fabra-ROA telescope project\cite{4} aims to refurbish an f/1 0.5m Baker-Nunn Camera (BNC) with 4096 × 4096 CCD covering a field of view of 4.4° × 4.4° for the robotic surveying purposes, this re-furbishing project is similar like the ARIES BN Schmidt telescope project.

The basic optical design of the Baker-Nunn camera at ARIES uses a three-element corrector to produce an extremely wide field of view (5° × 30°) across a curved plane at the prime focus for photographic imaging. The transformation of the Baker-Nunn camera into a 50 cm Schmidt telescope with CCD imaging capabilities is a process which comprises several steps in different categories. Major jobs in this project are (i) modification of optical design for curved to flat focal plane (CCD observations), (ii) changing the mounting system from alt-azimuthal to Equatorial english mount (mechanical re-designing), (iii) computer control of the telescope, (iv) optical alignment and installing new customize CCD imaging system.

2 Optics re-designing

To accommodate CCD detectors in the focal plane, the field should be flat. The optical design of the telescope needs to be corrected for flat focal plane as wide as possible with acceptable geometric distortion. The new design for Baker-Nunn Schmidt telescope incorporates two new optical elements, one field flattener lens and one meniscus lens, with old optical elements that include 80 cm f/1 primary mirror and 50 cm aperture 3-elements corrector lens system. The field flattener is used to flatten the curved field. The lens is 55 mm diameter double convex lens and placed inside CCD camera at distance 1.66 mm from the CCD chip to avoid from introducing unacceptable aberrations. A meniscus lens is placed between focal plane and primary mirror. The meniscus lens provides the correction for the astigmatism introduced by the field flattener. The optical layout of the BNC telescope showing new optical elements is shown in Fig. 1a.

The optical system of the Schmidt telescope consists of a 3-element air-spaced Schmidt corrector lens system with an aperture of 50-cm, a spherical primary mirror of 80 cm diameter. The optical elements and their positions in the telescope including some useful parameters are listed in the table 1.

3 Mechanical re-design

Schmidt Telescope has a spherical primary mirror of diameter 80 cm housed in primary mirror cell supported on 18 axial and 12 radial supports, which are balanced to support exactly the proportion of weight of the mirror coming on them at any position of the primary mirror. Primary Mirror cell is mounted at the bottom end of the tube. Baker Nunn corrector and the prisms are mounted on the front (top end) of the tube. They can be adjusted to align with the axis of

\footnote{http://www.am.ub.es/bnc/}
The optical performance were studied by optimizing all optical elements in the telescope and the operating wavelengths using the Zemax. Fig. 1b shows the
spot diagrams at the five semi-field points located at 0.00, 0.707, 1.00, 1.414 and 2.00 degrees from the center in the visible wavelength. The spot sizes are in the range of 35 to 50 µm over the entire field. The encircled energy (EE) of 90% is expected to lie within 30 µm diameter region up to 1.414 degrees of the semi-field, while 80% at the edges. Optical analysis shows that the field curvature would be less than 20 µm at the edges, and the distortion of about 0.09% at the edges. For a 18 mm semi-field size at the focal plane, a distortion of 0.09% corresponds to 16 µm.

5 CCD camera system

The CCD camera is located at the prime focus of ARIES Baker-Nunn Schmidt telescope, inside the telescope tube at about 521.77 mm from the primary mirror. The f/1 fast optics covers 4 degree circular field of view with the meniscus lens placed between CCD detector and primary mirror at 345 mm from the primary. To make a change from the curved to flat image plane, the modified optical design incorporates a field-flattener lens close to (in our system, it is 1.66 mm) the CCD chip. As the CCD camera sits inside the telescope tube at the prime focus, the outside dimensions of the camera have to be compact for minimum obscuration of the incoming beam from the primary.

The CCD detector is Kodak KAF-168003 chip with 4096×4096 pixels, each 9 µm size. The detector is used in the front-illuminated mode, the quantum efficiency (QE) is about 50-59% in the visible band. Technical specifications are shown in the table 2.

Table 2. Technical specifications of the CCD camera

| Specification                | Value                                      |
|------------------------------|--------------------------------------------|
| CCD chip                     | Kodak KAF-168003                           |
| Quantum efficiency           | ~55% at V                                  |
| Array size                   | 4096 x 4096                                |
| Pixel size                   | 9 µm                                       |
| Imaging area                 | 36.68 x 36.86 mm                           |
| Read Noise                   | 9-11 electrons                             |
| Dark current                 | < 1 electron/pixel/sec (at -30º C)         |
| Operating Environment        | temperature: -25º to 35º C. Relative humidity 10 to 90% |
| Cooling system               | Thermoelectric cooler with fan-assisted air cooling; operates 55-60 deg. C below the ambient temperature; and also the optional exchangeable liquid cooling |
| Linear Full well             | 100K electrons                             |
| Camera outer dimension       | 6.2 inch width x 6.2 inch depth x 4.2 inch height |
| Camera weight                | ~ 6 pound                                  |
6 Opto-mechanical alignment

The optical alignment of a Schmidt telescope requires the fulfillment of three simultaneous conditions: (1) to obtain the coincidence of the optical axis of the corrector plate with the geometrical axis of the tube, (2) to locate the center of curvature of the spherical mirror at center of the corrector plate, (3) to orient the detector plane (centering and tilting) according to its focal surface.

The following proposed alignment procedures could be followed as described by Anderson & Clausen (1974) [9]:

i. Proper placing of the primary mirror in the cell.
ii. Centering of the corrector elements.
iii. Removing of the detector tilt.
iv. Centering of the detector.

Table 3. Estimated throughput for the ARIES B.N. Schmidt telescope

| Optical components       | Transmission | Cumulative efficiency |
|-------------------------|--------------|-----------------------|
| 3-element corrector     | 0.9×0.9×0.9  | 0.729                 |
| Primary mirror          | 0.95         | 0.693                 |
| Meniscus lens           | 0.9          | 0.623                 |
| Field Flattener lens    | 0.9          | 0.561                 |
| Filters (V,R)           | 0.8          | 0.448                 |
| CCD QE                  | 0.55         | 0.246                 |
| **Total**               |              | **0.246**             |

Table 4. Parameters used for SNR calculation

| Parameter                              | Value         |
|----------------------------------------|---------------|
| Telescope diameter                     | 80 cm         |
| Clear aperture                         | 50 cm         |
| Plate scale                            | 412 arcsecond/mm |
| Readout noise of the detector           | 10 electrons/ADU |
| Dark current of the detector            | 1 electron/pixel/sec |
| Pixel size                             | 9 µm          |
| Saturation limit                       | 100000 electrons |
| Thoughtput of the system                | 0.246         |
| Sky brightness in V                     | 21.8 mag/arcsecond^2 |
7 Detection limit with the CCD

For a CCD, the signal to noise ratio (SNR) from a point source is determined by a well-known CCD equation [10], which is given by,

\[
\frac{S}{N} = \frac{N_{\text{star}}}{\sqrt{N_{\text{star}} + n_{\text{pix}}(N_{\text{sky}} + N_{\text{dark}} + N_{\text{read}})}}
\] (1)

Where \( N_{\text{star}} \) is the total photon counts from the star (sky subtracted), \( N_{\text{sky}} \) is counts from the sky. The \( N_{\text{dark}} \) and \( N_{\text{read}} \) are the dark current and read out noise, and it is the characteristic of the CCD. The \( n_{\text{pix}} \) is the total number of pixels contained within the selected aperture for the photometry, it is related to \textit{seeing} of the site. Here, star images are approximately 20 -25 \( \mu \text{m} \) in diameter, this spot size is a practical lower limit for the optical system. Considering the image size, \( n_{\text{pix}} \) is chosen to be \( \approx 3 \) pixels, corresponding to \( \approx 11 \text{ arcsecond} \) in the sky. The \textit{seeing} is \( \approx 2 -2.5 \text{ arcsecond} \) for our site, which is far below the spot size of an image.

The parameters, listed in the table 3 and 4, are considered for estimation of the SNR and shown in Fig. 2. The SNR is basically related to the photometric error, \( \sigma_m \approx 1.085/\text{SNR} \). The predicted magnitude limit is \( V \approx 19 \) for a 10\( \sigma \) detection and an exposure time of 300 sec. A photometric precision of 1\% (\( \sigma_{\text{mag}} \approx 0.01 \)) for a \( V = 15.5 \) star with exposure time of 100 sec is estimated from photon statistics from the star and the sky background. The theoretical limit of the maximum photometric accuracy from the system is related to the linear full well capacity of the detector, the limit here is 3 \text{ millimagnitude}.

8 Summary

We present here the development of ARIES Baker-Nunn telescope project, which is re-designed from a Baker-Nunn satellite tracking camera. The telescope will be used in a wide-field imaging mode using the custom designed CCD camera for various Astronomical research programs. The optical components in the new design, like field-flatterner lens and minicus lens, are procured from the standard optical companies. The custom designed CCD camera is in the processes of the procurement from the Finger Lakes Instrument, USA. The first-light from the telescope is expecting during the mid-2009.

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Fig. 2. The graph shows the predicted photometric precisions versus V magnitude for the different exposure times considering the parameters in the table 4. The horizontal line shows the signal to noise ratio (SNR=10) for the different exposure times. The bright end of those curves limit up to the saturation limit of the detector.

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