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Argos: An Optimized Time-Series Photometer

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Abstract. We designed a prime focus CCD photometer, Argos, optimized for high speed time-series measurements of blue variables (Nather & Mukadam 2004) for the 2.1 m telescope at McDonald Observatory. Lack of any intervening optics between the primary mirror and the CCD makes the instrument highly efficient. We measure an improvement in sensitivity by a factor of nine over the 3-channel PMT photometers used on the same telescope and for the same exposure time. The CCD frame transfer operation triggered by GPS synchronized pulses serves as an electronic shutter for the photometer. This minimizes the dead time between exposures, but more importantly, allows a precise control of the start and duration of the exposure. We expect the uncertainty in our timing to be less than 100 μs.

Key words. Photometer—CCD—time-series—variable—instrument.

1. Requirements for an optimized time-series photometer

To study phenomena variable at short timescales, we use a technique called relative time-series photometry or high-speed differential photometry. A good time series photometer not only requires a precise measurement of the start time of an exposure, but also the duration of the exposure. Besides accuracy in timing, it must be able to provide sufficient time resolution to sample the variable phenomena well. These requirements must be additionally satisfied by a photometer of high quantum efficiency in order to qualify as an optimized time-series photometer.

For example, to study the hot ZZ Ceti stars that exhibit pulsation periods in the range 100–300 s, we need a suitable time resolution of 5–10 s. We would require a photometer that allows a short exposure time and introduces an insignificant dead time between consecutive exposures. Frame transfer CCDs are ideal for time-series photometry as they can provide contiguous exposures with no dead time. Photometers with a high readout time are incapable of good time-series photometry, even if they allow a 1 s exposure time. We show the light curve of a pulsating white dwarf acquired using the low resolution spectrograph in imaging mode on the 9.2 m Hobby–Eberly Telescope at McDonald Observatory (Fig. 1). We used 7 s exposures to match the instrument dead

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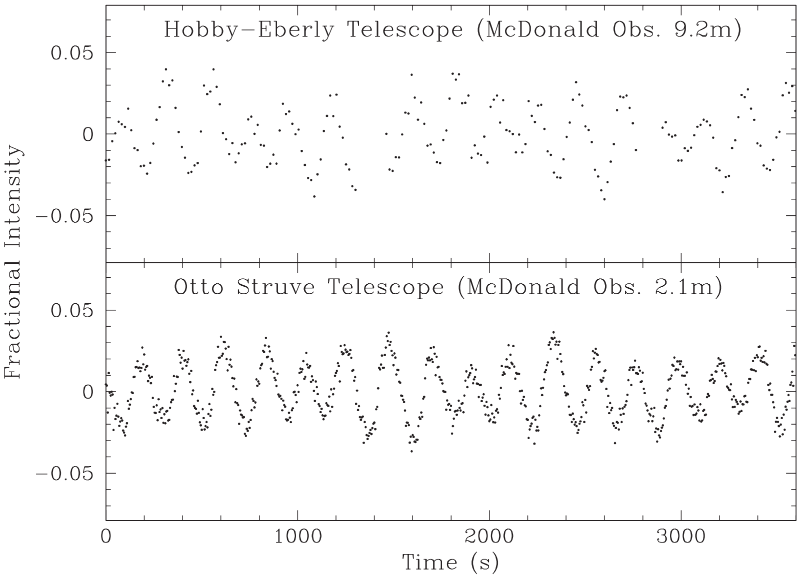

Figure 1. Light curves of a pulsating white dwarf acquired using the low resolution spectrograph on the 9.2 m Hobby–Eberly Telescope (top) exhibit uncertainties in period and phase larger by a factor of 1.5 than data obtained for the same time span using an optimized time series photometer on the 2.1 m telescope (bottom), also at McDonald Observatory.

time of 7 s. We also show observations of the same star using Argos (see section 2) with 5 s exposures on the 2.1 m Otto Struve telescope, also at McDonald Observatory. The data from the 9.2 m telescope exhibits uncertainties in period and phase larger by a factor of 1.5 than the 2.1 m data, acquired for the same time span (Mukadam 2004).

2. Argos: Designed for time-series photometry

We describe a high speed time-series CCD photometer, named Argos, designed for the prime focus of the 2.1 m telescope at McDonald Observatory (Nather & Mukadam 2004; see Fig. 2). One basic goal in the design of this instrument was to take advantage of the improved quantum efficiency that CCD detectors offer, so that we could obtain usable data on fainter stars than the Photo Multiplier Tube (PMT) instruments could measure, and data of better quality on those they could. We find that the CCD instrument is about nine times more sensitive than the PMT instruments used on the same telescope for the same exposure time (see Fig. 3). We can therefore find and measure variable white dwarf stars some 2.4 magnitudes fainter than the previous limit of magnitude 17.0, significantly increasing the number of such objects available for study.

A more long-term goal was to provide an instrument whose timing accuracy was high enough to allow a search for small deviations from the smooth secular change in pulsation frequency due to white dwarf cooling (e.g., Kepler *et al.* 2000), opening the possibility that such deviations, if found to be periodic, could demonstrate the presence of planet-sized objects in orbit around the white dwarf star (e.g., Kepler *et al.* 1991; Mukadam *et al.* 2001; Winget *et al.* 2003).

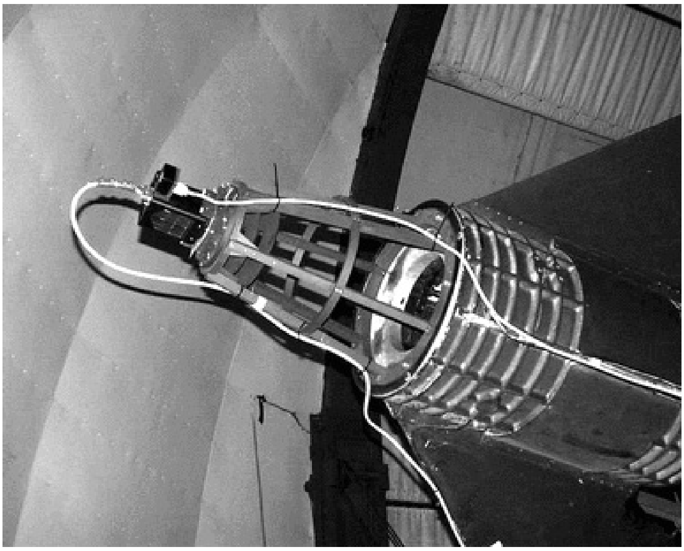

Figure 2. We show the CCD photometer Argos on its prime focus mount at the 2.1 m telescope at McDonald Observatory. Attached to Argos is a smaller CCD camera with a wide angle field of view (150°). It captures images of the dome slit at regular intervals, helping the user to decide when it is time to move the dome.

2.1 *The CCD camera*

Argos is based on a commercial instrument made by Roper Scientific, the Princeton Micromax 512 BFT NTE-CCD camera[2]. We list the specifications in Table 1.

Table 1. Summary of camera specifications.

Active area	512×512 pixels, each pixel size $13\mu \times 13\mu$
Frame transfer time	310μ s
Readout time	0.28 s, unbinned full frame
Measured read noise	4 electrons RMS at 1 MHz (16 bit A/D conversion)
Gain	2 electrons/ADU
Dark noise	1–2 ADU/s/pixel at −45°C (thermoelectric cooling)
Quantum efficiency	30% at 3500 Å, 80% 4500–6500 Å, 40% at 9000 Å
Linearity	$\sim$ 1% below 40,000 ADU (saturation at 65,000 ADU)

We acquire an image scale of 3.05 pixels per arcsecond (F/3.9) and a field of view of 2.8 arcmin × 2.8 arcmin for our 512×512 pixel CCD chip. Frame transfer, initiated by pulses from a GPS system, allows us to obtain contiguous exposures as short as 1 s. The CCD is back-illuminated for improved blue sensitivity and provides a quantum efficiency of 80% in the wavelength range 4500–6500 Å. With thermoelectric cooling, we maintain the chip at a temperature of −45°C, and obtain a dark current of 1–2 ADU/s/pixel. The readout time for the entire chip with no binning is 0.28 s; the readout noise is less than 8 electrons RMS.

[2]http://www.roperscientific.com/micromax.html

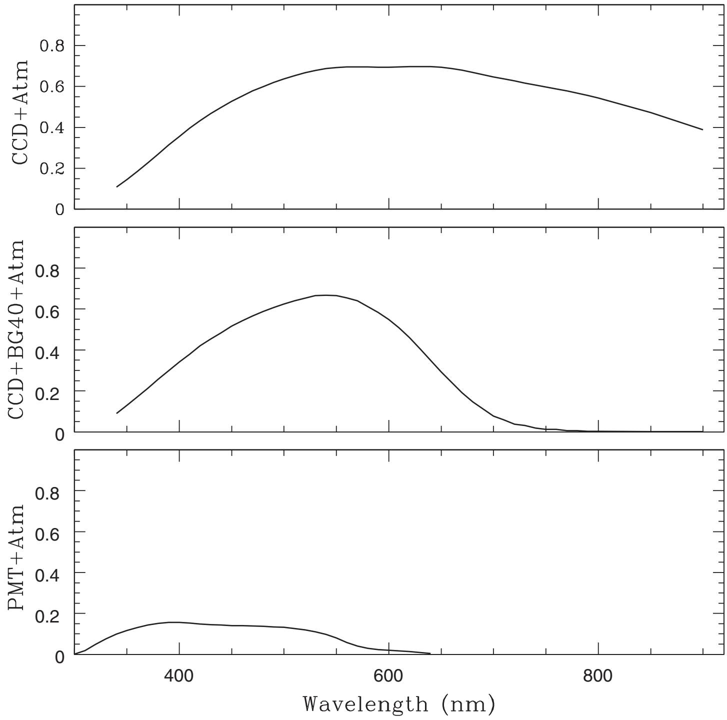

Figure 3. We show the wavelength response of the Argos CCD convolved with atmospheric extinction. The middle panel shows the modified response for a blue bandpass filter placed before the CCD. The lower panel shows the wavelength response of a PMT, a detector we used before Argos. The improvement in sensitivity of the Argos CCD *vs.* PMT is a factor of nine, as measured on the same telescope.

2.2 *Wavelength response*

We show the wavelength response of the CCD chip in the top panel of Fig. 3, taking atmospheric extinction into account (Mukadam 2004). We show the response of our instrument including a 1 mm BG40 Schott glass filter in the middle panel, while the bottom panel of Fig. 3 shows a PMT (R 647 Hamamatsu) wavelength response for comparison, convolved with atmospheric extinction. We used a PMT photometer, called P3Mudgee (Kleinman *et al.* 1996; Nather & Warner 1971), on the same telescope to gather data on pulsating white dwarfs before Argos.

2.3 *Instrument timing*

A time-series photometer must know precisely when an exposure started, and precisely how long it took. These are two different requirements, involving both a time epoch and an interval. The Argos timing system is based on a GPS clock designed primarily for precision timekeeping, although position information is also available. It consists of an oven-controlled crystal oscillator disciplined by signals obtained from a GPS receiver[3]. The time epoch is claimed to be uncertain by about 50 ns, considerably more precise than we need, but comforting.

[3]http://www.trimble.com/thunderbolt.html

We have assembled a simple count-down register on a small circuit card that can accept the 1 Hz timing pulses from the GPS clock, and can provide an output pulse to initiate frame transfer in the CCD camera (Nather & Mukadam 2004). The exposure intervals are thus contiguous, and determined directly from the clocking hardware. The jitter in the timing for this operation is hard to measure, but we expect it is $\leq 100\,\mu$s. The timer card plugs into the parallel port on the camera control PC, so the countdown value (*i.e.*, the exposure time) can be set into it from software. Thereafter it operates independently, initiating frame transfer operations at the established timing intervals. Exposure times can be set to any integral number of seconds from 1 to 30.

Immediately following a 1 Hz timing pulse, the GPS clock provides information from which the precise epoch of the pulse can be determined. The information arrives encoded in packet form at the serial port of the PC at 9600 baud, where it can be read and unencoded by the software control program. The PC serial port is buffered so that the epoch (the time and date) for each pulse can be determined even if a second packet arrives before the first one is read by the program.

A second clock, somewhat less accurate, is available if the camera control PC is running the Network Time Protocol (NTP[4]) software, which obtains timing information over the internet by periodically contacting time servers and adjusting the PC system clock accordingly. It allows for internet time delays as well as it can, and averages the best readings it finds to keep the system clock in proper synchronization. The Argos control program relies primarily on the GPS clock for timing, but can use the NTP-disciplined system clock if the GPS time signals are not available. For observer assurance, it compares the time ticks from the two clocks, and displays their time difference in a status display window. After both clocks have been running for a few hours, the time difference is usually within a few milliseconds.

Note that although the camera originally arrived with a mechanical shutter, we removed it and chose to use the frame transfer operation as an electronic shutter. Mechanical shutters introduce a timing jitter, undesirable in a time-series photometer. Besides, they have a lifetime of an order of a million cycles and we do not expect them to last long with high-speed photometry.

2.4 *The prime focus mount*

We show Argos on its prime focus mount in Fig. 2, at the 2.1 m telescope. Argos mounts on the focus assembly, and the entire photometer moves along the optic axis when we focus the telescope. Design considerations for the prime focus mount necessitate that the optic axis passes through the center of the 6 mm $\times$ 6 mm CCD chip, while the CCD plane remains perpendicular to the optic axis. We cannot rely on machining precision alone to center the optic axis on the chip, so we mount the camera on a plate that can be moved by half an inch in two orthogonal directions using x–y adjustment screws. These x–y axes align with the rows and columns of the CCD. We control the tip/tilt of the camera by a push-pull arrangement of screws, to orient the CCD perpendicular to the optic axis. We align the instrument every time the primary mirror is re-aluminized; Argos is sensitive to changes in the orientation of the optic axis larger than 24 arcseconds. When properly aligned, we expect the corners of the chip

[4]http://www.ntp.org

to show aberration from coma as a result of the parabolic primary mirror. This effect is calculated to expand a point image to about 1 arcsecond in diameter. We rarely experience sub-arcsecond seeing at McDonald Observatory, so we have not been able to verify this calculation.

2.5 *Baffling Argos*

Scattered light was initially a significant problem, and we chose hard (to corrode) black anodizing to eliminate the shiny aluminum surfaces of the mount. We also replaced the single crude baffle in the original design with a five-stage baffle system consisting of two thin baffles close to the camera, and three others in the body of the mount. The three baffles closest to the camera have square shaped apertures with rounded corners and are derived by projecting the light beam backwards from the CCD. Their apertures are a few per cent larger than the diameters of the light beam at those points. The other two mount baffles have circular apertures, which are 5–7% bigger than the light beam. The edges of all the light baffles are at an angle of 45° with respect to the optic axis to reflect light away from the CCD camera.

Our current images are flat to within a few per cent; the variations in the flat field come from structural non-uniformities in the CCD chip itself. This pattern is stable and can be removed, giving us residual variations of less than a per cent.

2.6 *The camera control computer*

The PC that controls the camera has fairly modest requirements by modern standards: it must have a PCI bus to accept the camera control card, a parallel port (for the timer card), a serial port (for the GPS packet information), enough memory to run the Linux operating system comfortably (256 MB is enough, but more is always better) and enough disk space to hold the images as they arrive (527 Kb each). Our current camera control PC runs a Pentium III at 1 GHz and is not pushed for time. The software prefers a display resolution of 1280×1024 so the various windows do not overlap each other. A 17-in LCD works fine. The PC also needs an ethernet card to connect to the internet, so the NTP software can discipline the system clock, and to receive pointing information from the computer that controls the 82-in telescope. This connection is also used to transfer image data to our Argos data archive in Austin (slowly), and to allow a remote login to run the camera for testing purposes (even more slowly).

We usually operate a second PC as well, with access to the disk on the camera control computer, so arriving image data can be examined by software not concerned with the data acquisition and recording process.

3. Controlling software

The control program is called Quilt 11 (q11), the most recent in a series of programs designed for time-series photometers (Nather & Mukadam 2004). The program also includes an online extraction routine, and displays the light curves in real time for the observer's perusal.

3.1 *Program requirements*

Once the camera has been set to operate in frame transfer mode, images arrive via direct memory access (DMA) at the end of each exposure and appear magically in memory. The program must first associate each image with its epoch (start time and date) before it is written to disk. This is not quite as straightforward as it sounds: a new exposure starts when a frame transfer operation finishes, so the epoch is available right away, but obviously the image is not—it's still being exposed. It only shows up after the next timing pulse (and its epoch) arrives, and then only after the readout process has finished. The program must account for this so that the proper epoch is associated with the appropriate image.

The data images are recorded in FITS[5] format, with the epoch and other operating parameters in the header. Each image has its own file, so the file name must be generated automatically and the names must be sequential so they can be kept in proper time order. In our design the images arrive whenever a frame transfer pulse is generated by the clock—that is, all the time. We display the images using DS9.

Once data recording starts (in response to the "go" command), the extracted light curves are displayed by the DS9 plotting widget. The observer must then act as an aide to the program to do things it cannot do for itself: keep the star images on the chip, keep the dome out of the light path, and be prepared to shut things down if it rains. In addition to plotting the light curve, the program also prints columns of numbers on the terminal used to start the program: the image number, the elapsed time, and the extracted brightness for each of the marked stars with sky removed. The last column shows the average sky value that was subtracted from the target.

3.2 *Software design*

The q11 program is written in the C language, and consists of 5 separate executable processes in simultaneous execution. It is designed to run on a PC under the Linux operating system and to tolerate the presence of other programs running at the same time on the same CPU. Both incoming time and image data are buffered to maintain proper real-time operation. Details of its architecture and the on-line extraction algorithms are presented in Appendix A of our published paper (Nather & Mukadam 2004).

The program can also run in simulation mode, without a telescope, camera or GPS timing system. Previously recorded data images are read from disk into the same buffer used by the camera, and the timing is simulated from the system clock ticks. Users can use this mode to review data previously recorded.

3.3 *Display*

The data acquisition and on-line extraction process runs in a thread separate from the display process because of timing considerations: the display routines (DS9 and its plotting widget) are written in Tcl/Tk, an interpreted language, and are therefore slow. At the shortest exposure times the acquisition process can easily keep up but the display routines cannot. Arranged as separate threads of execution, they run in parallel, so acquisition gets its needed amount of CPU time even if display falls behind. Should

[5] http://fits.gsfc.nasa.gov/fits_intro.html

this happen, the user still sees the printed luminosity values appear right away, but the plotted values appear in clumps, rather than one at a time, whenever the plot widget gets updated. No data points are lost. Display of some of the incoming images may be skipped, but the DS9 window always shows the most recent one when it is updated. The q11 program can run under any window manager, but users notice how much more slowly the display windows are updated using Gnome or KDE, compared with WindowMaker, which is smaller and faster.

4. Characterizing Argos

The measured counts for a star contain statistical photon noise, scintillation noise mainly due to turbulence high in the atmosphere, seeing noise due to turbulence close to the telescope, and modulations from varying atmospheric transparency. Sky counts also include statistical fluctuations, modulations from changes in transparency, etc. Noise in the stellar and sky counts add in quadrature to give us the observed noise in the reduced light curve. We show the root mean square (RMS) scatter as a function of magnitude for light curves of constant stars, with exposure times of 10 s each, in Fig. 4 (Mukadam 2004). Such a plot can be used to derive the expected photometric precision for a star of given magnitude and for a given exposure time by simple scaling. We determine the instrumental magnitude by comparing the counts of the constant star to the known white dwarf in the field. This method is not reliable for stars much brighter than the white dwarf.

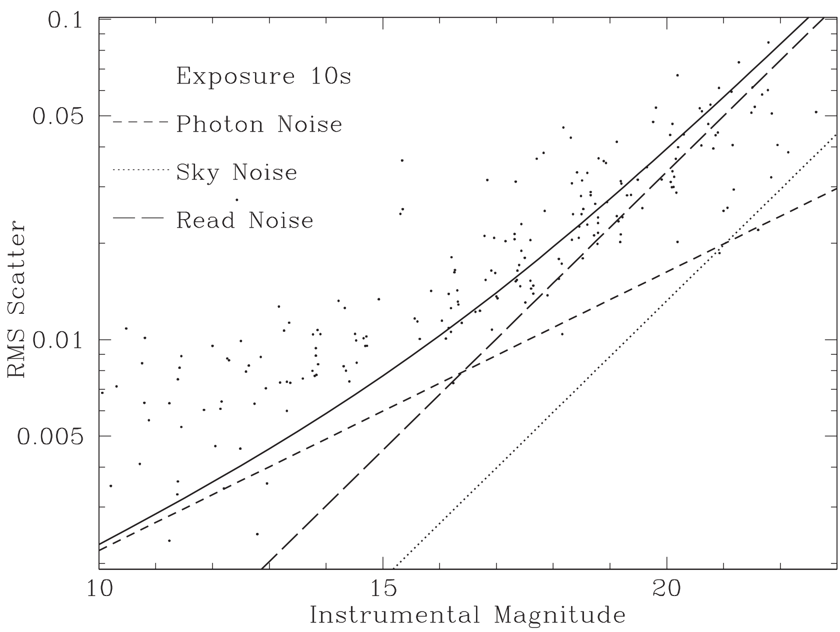

Figure 4. The RMS scatter in the light curves of constant stars shows photometric precision as a function of magnitude for 10 s exposures. Photon noise dominates the observed noise in bright stars. Noise in faint stars is governed by the quadrature sum of read noise and sky noise. For Argos on the 2.1 m telescope, we find this transition between “bright” and “faint” stars to be at 16.5±1.0.

Using the scintillation power spectrum published in Dravins *et al.* (1998), we estimate a 0.4% scatter in light curves of bright stars with exposure times around 1–3 s. We find the effects of low frequency scintillation and transparency changes mostly correlated (and hence removable) over the Argos CCD.

The scatter in Fig. 4 depends chiefly on the weather conditions, extinction, filters used, as well as magnitude and number of comparison stars in the field. Figure 4 shows a model of stochastic photon noise and sky noise, as well as read noise. Photon noise is the dominant source of noise for bright stars, while read noise and sky noise govern the floor for faint stars. The CCD specifications indicate a read noise of 8 electrons RMS, which would make the expected noise higher than the observed noise. By requiring that the quadrature sum of read noise and stochastic sky noise match the observed noise for faint stars, we measure a read noise of 4 electrons RMS. The magnitude at which we transition from a dominant photon noise to a combination of sky and read noise, helps characterize the sensitivity of the instrument. We determine this transition in the nature of noise to be at $g = 16.5 \pm 1.0$ for Argos on the prime focus of the 2.1 m telescope at McDonald Observatory (Mukadam 2004).

5. Results

Argos saw first light on 1st November 2001, at the 2.1 m telescope at McDonald Observatory, six months after we purchased the CCD camera from Roper Scientific. After struggling with initial problems concerning timing, scattered light, and so on, we slowly settled into an intensive program of observing 6 weeks every trimester. We discovered 35 new ZZ Ceti stars with Argos, mainly observing DAV candidates from the Sloan Digital Sky Survey (Mukadam *et al.* 2004). We discovered the faintest white dwarf pulsator known to date, a 20th magnitude DB variable, WD 0947+0155 (Nitta *et al.* 2005; in preparation). Argos was also instrumental in the discovery of optical bursts from a low mass X-ray binary MS 1603.6+2600 (Hynes *et al.* 2004), which confirmed that the compact object is a neutron star. We have achieved our long and short-term goals since the instrument has been in operation, and have established a list of target objects for the longer-term search for primordial planets.

The success story of Argos has also inspired a series of similar photometer designs at other sites such as Apache Point Observatory in the U.S.A., Indian Astronomical Observatory, and the Aryabhatta Research Institute of Observational Sciences in India. An Argos-clone (called Bargos) was used successfully at Siding Spring Observatory, Australia, on the 1 m telescope in support of a Whole Earth Telescope (WET; Nather *et al.* 1990) run in May 2002.

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