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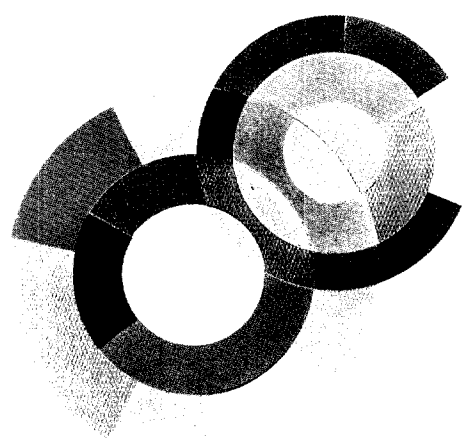
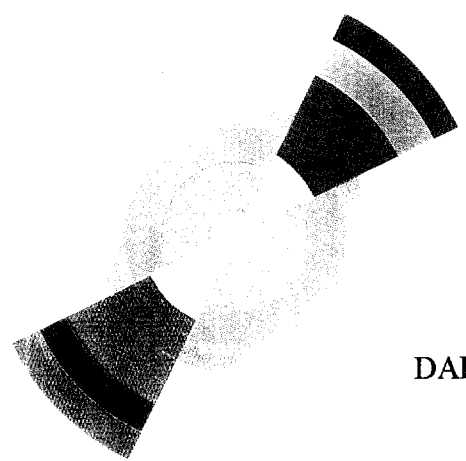
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THE TWO EROS 4K x 8K CCD MOSAIC CAMERAS

F. Bauer , J. De Kat

for the EROS2 Collaboration

DAPNIA

*Talk given at Optical Detectors for Astronomy ESO,
Garching (Germany), October 8-10, 1996*

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Abstract

We present our new astronomical wide field imager, which consists of two $4k \times 8k$ CCD mosaic cameras allowing simultaneous imaging in two focal planes with different color passbands. Each mosaic is maintained at 180K by using a fully automated original cryogenic system without LN2. A modular electronic system permits an individual computer controlled setting and a parallel readout of the CCDs. An acquisition system has been developed in order to treat the data rate of 10-15 Gbyte per night. The described instrumentation will be used in a sky-survey and -patrol to search for gravitational microlenses, supernovae and red dwarfs.

1 Introduction

The main scientific objective of the EROS 2 (Experience de Recherche d'Objets Sombres) collaboration is the search for dark matter in the form of massive compact objects such as Jupiters or brown dwarfs, which do not emit any detectable amount of light. Paczyński (1986) suggested that these could be found by the gravitational microlensing effect, which induces a temporary achromatic brightening of stars when the dark objects come close to their line of sight. As this transient effect is very rare, it is necessary to perform multicolor photometry of at least 10^7 stars over a long time-scale. Fields in the Galactic bulge, the Large and Small Magellanic Clouds offer the required high surface density of resolvable stars.

Our photometric detector should therefore be a wide field imaging system, taking images of the sky simultaneously in two color passbands on a dedicated telescope in the southern hemisphere. Electronics and data acquisition of the huge data flow must be rapid, in order to maximize the number of measurements per night. Pointing, dome rotation, and guiding should be done automatically.

2 Optics

The EROS 2 collaboration uses a dedicated 1m Ritchey-Chretien telescope mounted in the GPO dome at the European Southern Observatory, La Silla, Chile. Used until 1988 on the mount Chiran near the Observatoire de Haute-Provence it gave full satisfaction, before being decommissioned for budgetary reasons. Its two mirrors are made of Cervit.

For the present survey the mechanics has been completely refurbished and is controlled by a pointing and autoguiding unit. The usable field has been increased reducing the original focal ratio of F/8 to F/5, by using three focal reducers and two corrector lenses in each color channel. The optical assembly is shown in figure 1. Aberration, coma and astigmatism have been minimized to an acceptable level and spot diagrams show that 90 % of the light falls within a circle $30 \mu\text{m}$ in diameter. A dichroic beam-splitter permits simultaneous imaging in two focal planes with different color channels. The dichroic filter is sandwiched by two glass prisms in order to maintain his planarity and protection. The measured passbands of the system are 450-650 nm and 650-1000 nm. The focal length for both color is 5140 mm and the focal depth about $200 \mu\text{m}$ depending on the wavelength. The mosaic used covers $0.7^\circ \times 1.4^\circ$.

For applications other than the microlensing searches it is possible to insert manually filters in the two color beams. The available filters are V Gunn, i griz, r griz and a low pass filter at 900 nm.

As incoming light has traverses through 15 glass surfaces before getting on the detector, we had to make anti-reflection treatment on every surface. The total amount of reflected light after surface treatment should be around 10 %. A set of three diaphragms on each channel allows to avoid additional ghost generation. The average theoretical vignetting of the whole system is around 64 %, including the obturation of the secondary mirror.

A special wide field shutter system with an aperture of $12 \times 24 \text{ cm}^2$ was developed. It is mounted above the dichroic filter and allows simultaneous and equal illumination of the two wide field cameras down to 0.5 seconds. The shutter consists of a 98 cm long brascurtain with a rectangular aperture in its middle and is attached on two turnable cylinder blocks. A film of dark chemically deposited teflon coating covers the curtain and allows a smooth running.

A small mirror mounted before the shutter west of the scientific field reflects light to an off-axis optical visualisation system with the autoguider camera. The available field is $11.3' \times 11.3'$. As the guiding limit is around 15-th magnitude, this allows to be operational in the whole sky.

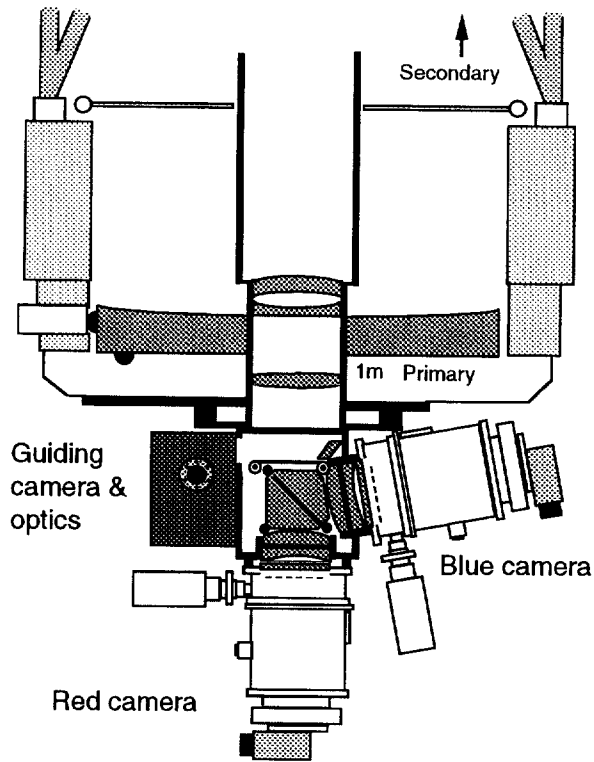


Figure 1: Technical view of the optical mounting

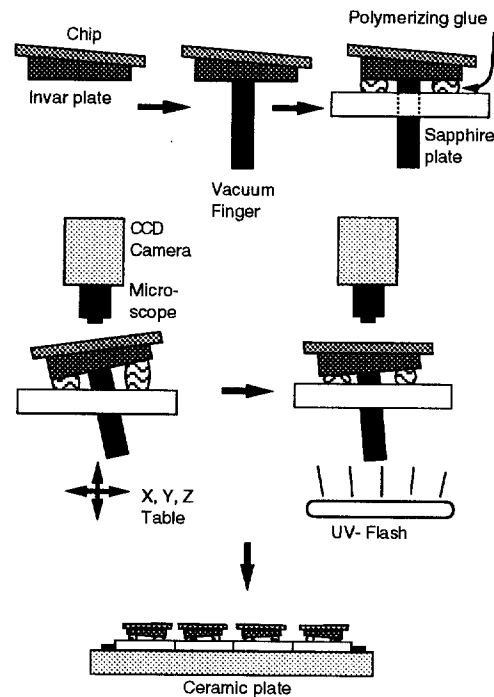


Figure 2: Mounting procedure of the CCD.

3 The CCDs

We use Loral 2k×2k three edge buttable CCDs. The CCD was designed by J. Geary and manufactured by Loral Fairchild Imaging Sensor company (Geary et al. 1990). The CCDs are built on 4 inch wafers, each wafer providing four 2k × 2k and eight 512 × 512 CCDs. Each foundry run produces 22 wafers. The cutting and packaging and the first tests at low temperature were made by M. Lesser (University of Arizona). Final tests were done in our laboratory. In a batch of 88 CCDs we found 32 dead on the wafer after production and 18 usable 2 years later. Six of them could be read correctly on both outputs.

Each mosaic consists of eight thick Loral 2K3eb CCDs. The mosaic configuration is 2 × 4 CCDs and covers an area of 6.2 × 12.4 cm² (see figure 3).

Each CCD has one serial register with two low noise outputs at each end. A redundant design allows to read the whole CCD on one or two outputs. This turned out to be very useful and allowed us to use even CCDs with an defective output. The three phases imaging zone can be used in MPP mode, in order to reduce the dark current level.

Except cosmetic defects like bad or bright columns, or clusters, we encountered many problems in our batch. The pressure used for the wedge bonding had to be very low (40 g), due to a local fragility of the chip.

Many chips suffered of poor serial charge transfer efficiency (CTE). It was sometimes possible to use this device when the CTE in the other direction was alright. In other cases higher voltages on the serial clocks could improve the transfer at the cost of increased readout noise. For some devices a multiparameter and time-consuming optimization was necessary. In a smaller fraction we observed parallel or partial CTE problems. Sometimes the CTE was deteriorated at high light flux and lowered the available dynamic range. We noticed an important correlation between a bad serial CTE on the left amplifier and the position of the device on the wafer.

Many devices had offset or gain problems on their amplifiers. We could again find a correlation with the wafer-position.

Table 1: Characteristics of the 16 CCDs used for both mosaics. The number of dead columns are shown under DC, bright columns under BC, patches under P.

CCD N°	noise in e ⁻	dynamics in e ⁻	cosmetics			usable outputs	comments
			DC	BC	P		
R0	6.5	75000	1			right	1 LED
R1	8.7	105000	3			left	2 LED
R2	22.6	72000	3			left	fault line of 360 pixels, amp has no more gain
R3	6.4	85000	3			left	
R4	6.6	82000	4			both	
R5	6.4	85000	3	1	1	both	
R6	6.4	76000	7			right	
R7	6.7	91000	5			left	partial bad left CTE (7% lost) + 1 LED
B0	7.4	64000	7			both	
B1	6.0	90000	21			right	
B2	5.9	75000	13			left	
B3	6.1	90000	9			left	
B4	6.3	80000	10			left	
B5	6.1	78000	4			right	
B6	6.7	100000	9			left	
B7	6.2	74000	3		1	both	big cluster + ripples (7.7% lost)

In some cases the readout on only one output revealed rippled structure formed by abnormally noisy columns. This disappeared when the CCD was read on both outputs. No way to suppress this phenomenon could be found.

Three CCDs presented a partial horizontal fault line of some hundred pixels. Behind this all the sensitive area was lost due to bad CTE. The length of the fault line can be reduced by an increased parallel clock voltage or a slower parallel shift. This phenomenon could be explained by an abnormal high local impedance on a single Φ_p electrode.

The most spectacular problem was an LED effect in the serial register of some CCDs. During long integrations in the dark, one pixel of the serial register emits photons in all directions. Local saturation can be reached after 20 minutes. Fortunately this phenomenon decreases exponentially with distance.

4 Mosaic mounting

As the delivered CCDs mounted on invar-plates have different thicknesses, we used the assembling technique proven in the EROS 1 experiment (Arnaud et al. 1994a), shown in figure 2.

Each CCD has to be glued on a different sapphire plate, slightly larger than the CCD itself. This allows us to control the planarity of the lower sapphire plate surface and the upper part of the CCD, to avoid touching once the CCDs are put together, and the replacement of a single CCD in case of failure. The gluing was made with a dedicated machine designed by the optical detector group of DAPNIA Saclay using UV polymerizing glue (Charlot et al. 1996).

The sapphire plate is fixed on a plane XY table. The CCD is fixed on a vacuum finger, that goes through a hole in the sapphire plate. UV polymerizing glue is applied between the sapphire and the invar plate. The vacuum finger can be rotated and translated in every direction in order to achieve the best parallelism between the CCD and the sapphire plate. The planarity of the CCD is controlled by focusing a microscope with a CCD camera mounted on its top. For this purpose a special control software running on PC has been developed. Once the optimal position is achieved a UV discharge lamp is used to polymerize the glue. The main reason to

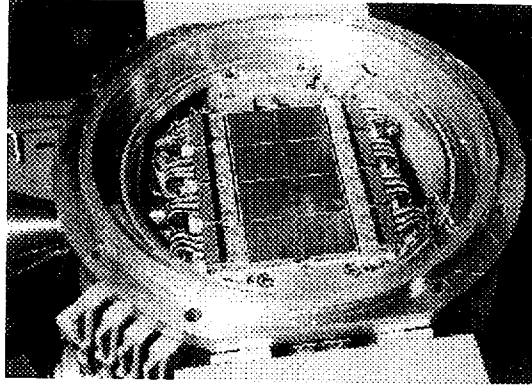


Figure 3: A view of the blue mosaic mounted in the cryostat

use sapphire is its good UV transmission ability.

All those plates are then bolted side by side on a ceramic cold plate. The sapphire and the ceramic material are delivered with a planarity better than $5 \mu\text{m}$. A very low pollution is needed in order to avoid radioactive noise. The coplanarity of the mosaic has a σ of about $\pm 10 \mu\text{m}$ and the inter-chip alignment is better than 2 pixels. The average gaps between two adjacent CCDs is 0.5 mm.

5 Cryogenic mounting and controlling

Each mosaic has to be maintained at most at 180K, in order to reduce thermal readout-noise. As a LN2 dewar would not fit between the telescope fork and due to the LN2 filling problems in EROS 1, we designed a new cryogenic system which does not use LN2 (see figure 5).

The cooling system of each camera consists mainly of a 15 kg block of pure aluminium, a thermal resistance, a 1 kg block of copper which supports the CCD mosaic and a commercial one stage cold head. This system is packaged in a vacuum chamber of dewar. This system has a continuous two steps operating cycle. First, during the off-survey periods, the cold head is run and connected to the aluminium block to cool down. The final temperature is close to 50 K. Secondly, throughout the survey period, the cold head is shut off and disconnected from the aluminium block. The main benefits of this method are to avoid use of LN2 and also to remove induced vibrations of the cold head during the observations.

During the whole time, the thermal resistance controls the temperature of the copper block and the CCDs, close to 180K with an accuracy of $\pm 0.1\text{K}$. This component of great importance is inserted between the copper block and the aluminium one. It directs the incoming heat-flows to the aluminium block. It is made of one circular plate fixed on the aluminium block by an epoxy knee joint and connected by copper flat spring-strips to the copper block. The inner part of the plate is covered with 900 flexible copper contacts. The thermal resistance value is controlled by varying the contact surface between the plate and the aluminium block according to the incoming flows and the state of charge of the aluminium block. The autonomy is 12 hours with a thermal stability around 0.1K. The aluminium block is cooled with a rate of 15K/hour.

All electrical connections in the inside chamber are made of manganin wires which reduce considerably thermal losses by conduction effects. The inner walls of the dewar are covered with super-insulated aluminized mylar. The inside pressure is around 10^{-5} hPa. Three electric heaters inside the dewar are used when the vacuum pumping runs in order to improve the cleaning out. A small electric heater fixed around the entrance window is designed to avoid condensation on the window surface.

Early in this project, a thermal model was developed in order to get a suitable compromise between the mass of the camera and the system time range and to simulate the feedback control laws with the purpose of checking the closed-loop system behaviour. The thermal model and terminology were established and drawn with electrical system's concept (see figure 4).

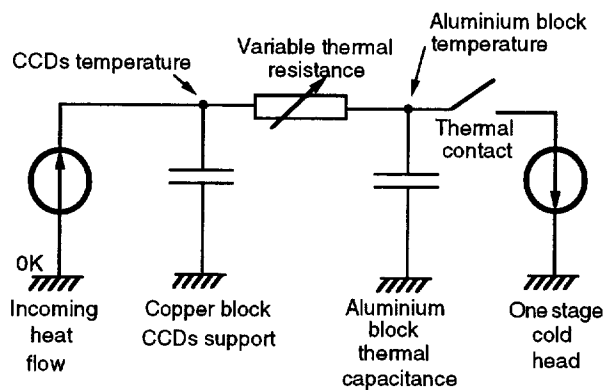


Figure 4: Electrical analogy of the cryogenic system. The grounding potential/temperature is set to 0 Kelvin. The incoming heat flow is mainly due to radiation through the entrance window

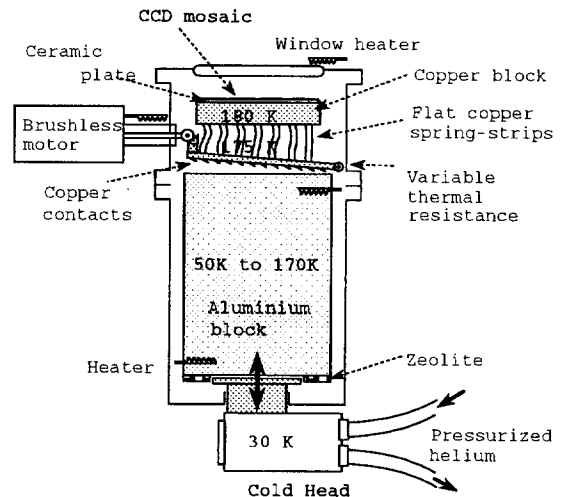


Figure 5: A schematic view of the cryogenic system

This model was used during the design and setting phases of the project. An automatic control system was designed and built to operate the wide field shutter and the cryogenic systems for the two cameras. The system is powered by an uninterruptible electric power supply. All the system is under the control of a Programmable Logic Controller (PLC) manufactured by Cegelec and General Electric- Fanuc (ALSPA 8000 serie). This machine is fitted with axis positioning modules, communication modules and discrete and analog input-outputs modules. The PLC is connected with the VME acquisition crate by a serial RS422/RS485 link with RTU protocol. The PLC is also connected with a monitoring personal computer compatible PC. It works as a database which stores relevant information to the control system with a sampling period of 30 sec. It is connected to the Internet network as a server thus allowing a remote control of the automatic processes. In this way, the engineering staff in France gets database files to analyse and repair the system in case of failure.

6 Electronics

The specifications for the EROS 2 electronic controller takes into account the experience achieved in EROS1 (Arnaud et al 1994b). The design should be more modular and flexible in order to be able to use any type and number of CCD with various output numbers. The readout of the $4k \times 8k$ mosaic should be faster (the EROS1 controller would take 9 minutes) with a lower readout noise. Furthermore great care should be devoted to reliability and CCD overvoltage-protection.

6.1 Organisation

Each camera has its own controller and VME acquisition system, linked together by a 40 m long pair of optical fibers. The controller is fully independent. He has its own power supply and also a digital signal processor (DSP) and all necessary data for the CCDs sequences. In stand-by mode he cleans continuously the CCD. The DSP controls the driver boards located in the same crate. Each driver board generates the polarization and clocking levels for every CCD. These levels are transferred to the cryostat by shielded cables. There, small filter boards are mounted near the CCDs, in order to eliminate interference and overvoltages. The analogic CCD output signal is transferred by twisted shielded pairs to the ADC crate located outside the cryostat, which

contains an analogic backplane, the ADC boards and an interface board to the DSP. Every ADC board contains two chains consisting of an amplifier, an ADC converter and an optocoupler interface. The pixel data are read by the DSP through the interface Xilinx board and transferred toward the VME through one of the optical fibers. There, a custom board called MMB (Memory Management Board) descrambles the data flow in real time and put it in a RAM-board. The mosaic image is then available for visualization, archiving and treatment. The separation of the functions in different boards allow a great modularity. Depending on the mosaic used, the system is assembled by modules and then described in the software of the acquisition. The theoretical limit is 64 CCDs with 4 outputs each, not taking into account problems due to power dissipation, power supply, weight and others. At present the EROS2 controller is optimized for one DSP and eight CCDs with one output.

6.2 CCD control

The DSP board does the sequencement of all the CCDs simultaneously. Its executable program can be loaded at any time from the acquisition VME station. It is possible to change easily the sequences but also to imagine other forms of sequencements, in order to repair unplanned CCD problems or to reduce contamination by blooming for example. This can be done without any modification in the hardware and without cutting off the power supply.

The driver boards are not designed for a special CCD type. They contain enough channels with large voltage-range to be adapted to any large scientific CCD array. With 32 8-bits DACs every driver board can generate up to 16 independent polarization voltages between -16 and 28 V and 16 clocks with levels between -16V and 16 V. This allows to switch instantly from MPP to non-MPP mode for example, or to optimize easily the control voltages for each CCD. This turned out to be very useful, since, for example, in the red camera only one of the eight CCD has the nominal voltages applied... Furthermore optional current buffer and slope control are available for the parallel clocks. All the voltage ranges are defined by resistances, in order to protect the CCDs against erroneous voltages requested by the user or software errors.

A daughter board can be plugged on the driver board. Thirty-two 8-bits ADCs redigitize the driver output levels, which can then be checked by the VME via the DSP.

In the cryostat each CCD is protected by a small filter board with Zener diodes against overvoltages induced by cabling errors, power supply or component failures.

The only parts of the system specific to a CCD type are the resistance supports on the driver boards, the filter boards, the connections inside the cryostat and of course all the files describing the system.

6.3 Analogic part

Very early in the project we decided to remove the whole analogic readout chain outside the cryostat, in order to have easy access and to facilitate tests. As a consequence we had to give special attention to the transportation of the CCD output signal to the preamplifier. For this purpose we use a 15 cm long twisted shielded pair in the cryostat. The analogic backplane, where the ADC boards are mounted, is directly plugged on the cryostat connectors. Even on the analogic backplane the critical strips pass between grounded strips and are sandwiched by grounded planes, in order to reproduce shielded pairs.

Each ADC board contains two channels. Each channel begins with a 10 k Ω CCD loading resistance followed by a coupling capacitance. Then a low noise preamplifier can be used in differential or single mode. Due to the clean connections to the CCD, the single mode turned out to be sufficient. The electronic gain is 30, with a bandpass limited to 2 MHz.

A clamping stage creates a new DC level after the amplification and does at once the subtraction of the CCD floating level. Special attention was given to this module, in order to avoid additional noise.

The ADC is a true 16 bit converter (Crystal 5101) with a conversion time of 8.8 μ sec. Our main reason for this choice, was its small dimension and power dissipation (300 mW), which are important parameters in a multichannel controller mounted in the Cassegrain focus. The serial output of the converters allowed to cut easily the ground loops by means of optocouplers. Furthermore each ADC board has its own isolated DC/DC power supply.

Once the whole control system is assembled, only one electric reference potential exists and is connected to the metallic mass of the whole telescope on one point near the CCDs. Moreover the reference potential has to be as homogeneous as possible between the CCD and the ADC. It was also necessary to protect the critical analogic signals against digital and other variable signals. As an example, we had to move the wire of the temperature

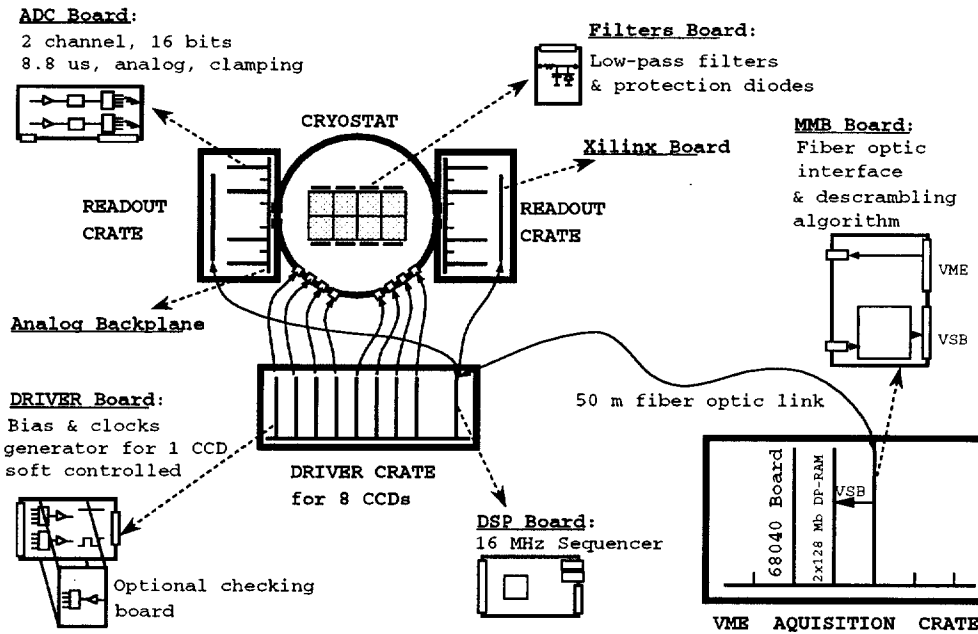


Figure 6: The electronic mounting

sensors in the cryostat, because interferences on them were cross-talking with the wires of the CCD signals. The measured readout noise is $6-7 e^-$ for all the channels, CCDs included, reading at 83 kpixels/sec. The readout noise of our two multichannel cameras is comparable to other single CCD cameras, using Loral devices of this generation. No cross-talk could be seen down to 10^{-5} .

6.4 Readout

Our goal was to read the mosaic as fast as possible, while sequencing the CCDs as slowly as possible. So we chose a pipeline method. In parallel, pixel n is shifted to the CCD output, pixel $n-1$ is preamplified, the ADC converter digitizes pixel $n-2$ and the DSP reads and sends pixel $n-3$ on the optical fiber link. The third operation gives the first time limitation and takes $8.8 \mu\text{sec}$ for the conversion in the ADC plus $2 \mu\text{sec}$ for memorisation on the Xilinx board and $1.2 \mu\text{sec}$ for varied operations in the DSP. Note that the analogic subtraction realized by a clamping system allows a CDS operation with only one conversion. During these $12 \mu\text{sec}$ the DSP has just enough time for the broadcast sequencing and the transmission of the $n-3$ pixel data of the eight CCDs. This necessitates good optimisation of this critical loop in the DSP assembling software. Furthermore the CCDs are only clocked at the rate of 83 kpixels/sec and the noise contribution remains low.

The Xilinx custom board executes the simultaneous serial-parallel conversion of up to 16 output channels. A Memory Management Board (MMB), connected at the other end of the optical fibers in the VME crate, unscrambles the mosaic pixel data-flow and sends it to memory-boards via a VSB bus. The pixel addresses in image memory zone are computed in the MMB board by a hardware-designed unscrambling algorithm, which is programmable following the organisation of the mosaic, the number and type of CCD and outputs. This allows the writing of the incoming image directly in the correct order, at the speed of 300 ns per pixel. We read the 64 Mbytes of the mosaic consisting of eight CCDs (using one output only) in less than 50 seconds, unscrambling included.

6.5 Implementation

As the controller is mounted at the Cassegrain focus, we had to take into account the dimension, weight and power dissipation constraints. So we had to miniaturize all the boards and to use as much as possible surface

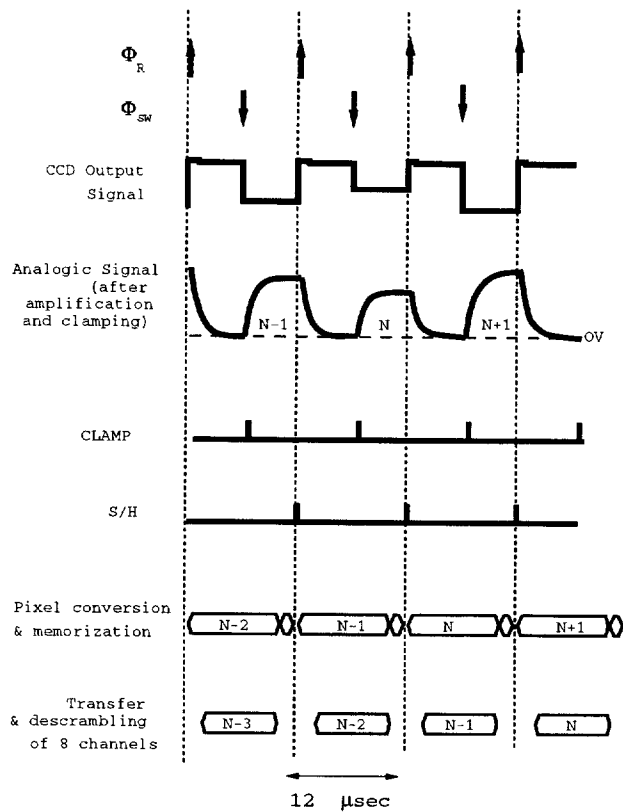


Figure 7: The pipeline principle

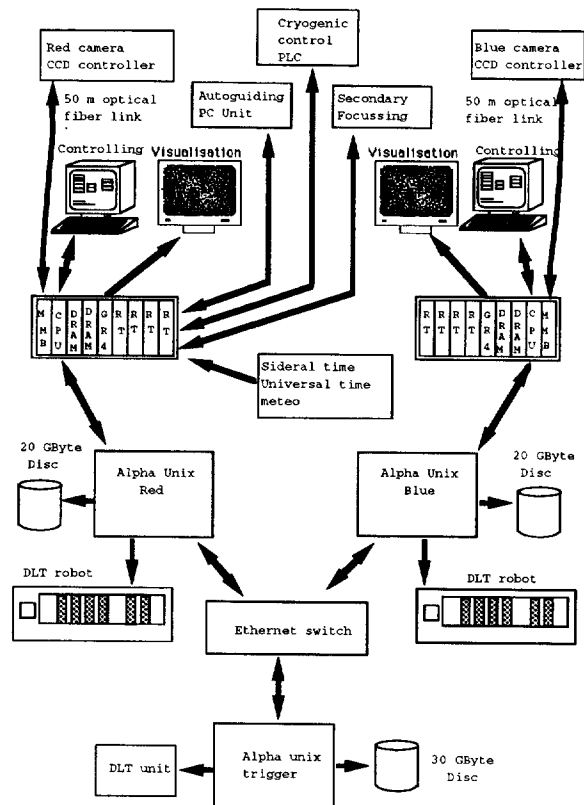


Figure 8: Data acquisition

mounted components. Every camera has three crates: one commercial single-europe crate hosts one DSP and driver boards plugged on a commercial backplane. The other two are custom crates which contain four ADCs and one Xilinx boards plugged on a custom analogic backplane. For every camera the controller system weights 15 kg and dissipates 100 W. The power supply is deported under the telescope floor, where the dissipated power is extracted by electric fans through a tube outside the dome.

7 Data acquisition

Due to the enormous data rate expected (5–8 Gbytes per night and per camera), we decided to divide the acquisition into two channels, one for each color. Every acquisition chain consists of one VME crate with a controlling and an imaging monitor and one Alpha DEC station with 20 GBytes of disc and a DLT-tape robot. They are located in a counting room 25 m away from the telescope.

Each VME crate contains the same software, which permits full control of the whole experiment. Both crates may be independent or synchronized, depending on the data to be acquired. Each VME is connected by Ethernet to an Alpha DEC station running with Unix. Once the images are treated by the VME, they are sent in FITS format through the Ethernet. The actual rate is one 64 Mbyte-image every 3 minutes. A switching bridge isolates the network traffic on each of the two channels. There second-level processing as well as data quality checks, flat-fielding are run. Optionally the raw data can be archived directly by means of a tape recorder mounted on the VME. The data is finaley archived in FITS format on DLT tape in order to perform the final photometry in a computing center in France. The two acquisition chains communicate with a third Alpha DEC station with 30 Gbytes of disc. This station is used to do a raw photometry of images of the previous night

in order to trigger on ongoing microlensing or supernova events and to alert the community before the next night.

Each VME work-station consists of a standard screen for the dialog by means of windows with menus and a graphic screen 1200×1024 for display of the images. We built the acquisition system by assembling commercial boards in the VME/VSB crates. A Motorola M167A (68040 @33 MHz) controls our custom MMB, two 128 MBytes Double Port VME/VSB Memory boards, visualization, I/O interface and other development boards. A local disk contains the system and the custom acquisition software, running on the real time operating system OS9. Below the control-command process, ten other background processes have to run simultaneously in order to control directly the electronics, visualization, data transfer to the DEC alpha station, but also the shutter, cryogenics, guiding and pointing of the telescope, via independent subsystems. Acquisition data like cryostat temperatures, telescope position and focussing, weather conditions are centralized at this level. A number of tools for the survey and interpretation of the images is also available in this system.

8 Summary

The whole system saw first light in June 1996 and became fully operational on July 1996. This wide field imager consists of two $4k \times 8k$ CCD mosaic cameras allowing simultaneous imaging in two focal planes with different color passbands. Each mosaic is made of eight $2k \times 2k$ three edge butttable thick CCDs developed by Loral/U.Arizona. Special manufacturing techniques allowed us to reach a gap between two CCDs of about 0.5 mm and a planarity of the entire mosaic with a σ of $10 \mu\text{m}$. Each mosaic is maintained at 180K by using a fully automated original cryogenic system without LN2. The cameras are mounted on a 1m Ritchey-Chretien telescope, at the La Silla ESO Observatory in Chile. The developed optics has a usable field of $0.7^\circ \times 1.4^\circ$. A modular electronic system permits an individual computer controlled setting and a parallel readout of the CCDs. The readout noise is around $6-7 e^-$, the cross-talk better than 10^{-5} , when digitizing at 83 Kpixels/sec. The resulting 64 Mbytes per mosaic are transferred with optical fiber to a VME acquisition crate, which includes an user interface. The data rate of 10-15 Gbytes per night is then reduced and treated by a pool of three DEC alpha stations.

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