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Part I : Mechanics, Optics and Cryogeny

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Abstract

A 20 cm^2 CCD mosaic camera has been especially built to search for dark galactic halo objects by the gravitational microlensing effect. The sensitive area is made of 16 edge-buttable CCDs developped by Thomson-CTS, with 23x23 μm^2 pixels. The 35 kg camera housing and mechanical equipment is presented. The associated electronics and data acquisition system are described in a separate paper. The camera resides at the focal plane of a 40 cm, f/10, Ferson reflector. The instrument has been in operation since December 1991 at the La Silla Observatory (ESO).

1 Introduction

It is widely believed that the flat rotation curves of spiral galaxies like our own indicate the presence of a halo of dark matter [?]. This matter may well consist of jupiters, brown dwarves, black holes, etc., generally called Massive Astrophysical Compact Halo Objects (MACHOs). In 1986, Paczyński [?] suggested that a population of such objects could be detected by a gravitational microlensing effect which induces a transient brightening of distant stars when a MACHO passes near their line of sight. The probability that a given star of the Large Magellanic Cloud (LMC) suffers a measurable microlensing with an amplification higher than 30 % is about 10^{-6}, assuming a spherical isothermal halo of 4 x 10^{11} solar mass. The time scale of microlensing can be very short and thus requires frequent sampling of the stars brightness. The typical duration for microlensing events depends on the mass of the unseen object, being about an hour for m = 4 x 10^{-4} solar mass ($M_{\odot}$), and about a year for m = 30 $M_{\odot}$. Sensitivity to large masses requires daily sampling of more than 10^6 stars while sensitivity to smaller masses requires an even more frequent sampling of a smaller number of stars (10^5).

The EROS collaboration (Expérience de Recherche d'Objets Sombres) decided in January 91 to cover the mass range $10^{-7}M_{\odot} < m < 10^{-1}M_{\odot}$ with two programs : one using Schmidt plates of the LMC to cover the high masses and one with a CCD mosaic on a dedicated telescope to be sensitive to the deflector masses in the range $10^{-7}M_{\odot} < m < 10^{-3}M_{\odot}$.

As an instrument of appropriate specifications for this purpose was not available in 1990, we decided to build a large area CCD camera. In this paper, we describe the whole set-up and mainly focus on the camera itself : CCD mosaic construction, camera housing and various equipments. A companion paper describes the electronics, data acquisition and performance.

2 Overview of the instrumental set-up

Fig.1 shows a scheme of the instrument.

2.1 Telescope

Because of the low probability of microlensing, the search for MACHOS is bound to last at least a few years an thus needs a dedicated telescope. A solution was found by the use of a 40 cm, f/10 Ferson reflector borrowed from the Observatoire de Haute Provence (OHP).The field of the telescope has been increased to more than a degree by installing a catadioptric combination of two lenses in place of the secondary mirror, and a field corrector curved plate used as the entrance window of the cryostat, just in front of the CCD mosaic.

The images are sampled by pixels of 23 μm x 23 μm. This size is near the maximal "pixel scale", i.e. the solid angle of 1 $arc.sec^2$ subtended by one CCD pixel, which is roughly equal to the third of the seeing disk area.

A survey of 10^5 stars per image requires then more than 10^6 pixels, a number which has been accomodated by building an array of 16 buttable CCDs developed by Thomson-CTS. The 16 CCDs mosaic has 3.7×10^6 sensitive pixels. The camera will be described in detail in the following sections.

2.2 Cryostat

The CCDs have to be operated at 170 K in order to eliminate the dark current. An LN2 dewar able to guarantee a hold time of 10 hours has been associated with the camera head unit, especially built to maintain the full CCD mosaic at this temperature. The head unit contains the amplifiers, one per CCD, which boost the CCD signal output and transmit the resulting signal to an outside command card.

2.3 Shutters, filters and focal position commands

Due to the large area covered by the CCD mosaics, a special shutter and filter assembly was built. The shutter opening is arranged to ensure a uniform illumination of the CCDs, down to very short exposure times. A 3-positions filter plate is associated to the shutter system.

The secondary optics of the 40 cm reflector is not movable along the optical axis, so the adjustement of the mosaics on the focal plane is performed by moving the whole camera with respect to the back plate of the telescope by means of 3 motorized screws. Each screw can be moved alone to optimize the orthogonality of the focal plane with respect to the optical axis.

2.4 Readout and storage of the data

A forthcoming paper will describe in detail the hardware and software used to read the CCDs and process the images.
The command cards, one per CCD, are located in 2 boxes just outside the cryostat. The output of the parallel readout of the CCDs (8 Mbytes of data per image) is transmitted to a VME command rack by 2 optical fiber serial links. A MC 68030 processor from Motorola (MVME 147), located in the VME crate is used to control the experiment and to manipulate and store the CCD images. A graphic system with a 1200 x 1024 screen bit mapped in a VME board can display the CCD images in several maps and visualize the part of image involved in each manipulation. The raw CCD data is stored on DAT tapes in the UNIX "tar" format.

3 The Thomson THX 31157 buttable CCD

When the decision was taken to build a large sensitive area camera, there were few prospects among several manufacturers to produce devices of 2000 x 2000 pixels. The appearance time on the commercial market was uncertain. An earlier agreement between Thomson, ESO and INSU (CNRS) led to the construction of a buttable CCD (THX 31157) derived from the TH 7882, a front-illuminated device with 579 x 400 pixels of 23 microns square size.

The THX 31157 is buttable on 3 sides, with a narrow (100 microns) dead zone on three sides. The CCD is glued on a ceramic base narrower than the sensitive area with the exception of the fourth side where the connectors are located ; they are followed by a flexible board (fig.2).

On each CCD, four fiducial crosses are added on the corners of the sensitive area to help in the alignment process.

4 Mechanical construction of the 16 CCDs array

The mounting and alignment of individual buttable CCDs on a ceramic plate was an important step of the project. A CCD can be replaced in case of failure; so each CCD is glued on its sapphire plate and all those plates are bolted side by side on a ceramic cold plate. Requirements about sapphire and ceramic materials are very specific : very good planarity (less than 10 microns) and very low impurity rates to minimize radioactive elements that could generate signals in the CCDs.
All CCDs have to be placed with the minimum gap between sensitive areas in order to reduce dead zones on the overall image. The target coplanarity of the different CCDs was specified so that the maximum deviation from the mean image plane of the mosaic should be smaller than 60 microns, which corresponds to a third of the focal field depth. The specification for the inter-chip pixel alignment precision was less than 1 pixel, or about 20 microns over the whole area of the mosaic.

To satisfy all these requirements the gluing operation needed a special machine. This machine was designed by the OMP Toulouse [?] and by the Optical Instrumentation Group at ESO. The CCD is placed on a vacuum finger that goes through a hole in the fixed sapphire, this one is maintained on a table under a microscope fixed on micrometrics XY tables to control the gluing operation. The vacuum finger can be rotated and translated in all directions to place the CCD parallel to the sapphire plate. A drop of UV curing glue is placed between the CCD and the sapphire and, when the optimal coplanarity is achieved, a UV discharge lamp is used to polymerize the glue and fix the CCD in its position. A special study led us to choose a glue with minimum shrinking and ability to resist low temperatures.

The 16 CCD are then bolted on the ceramic baseplate. The array is shown in fig.2.

5 CCD camera housing and cryogenics

The following requirements guided the design of the camera :

- the ability to ensure a hold time of about one observation night, in order to avoid perturbations during the data taking.
- the lowest possible mass, to minimize mechanical stresses, and dimensions compatible with the telescope mounting structures.

The 16 CCDs array is mounted precisely on a ceramic plate which is fitted and thermally coupled to a copper block within the cryostat vacuum upper section ; the vacuum reaches 10^{-5} mbars when the system is operated with liquid nitrogen providing internal cryogenic pumping. The temperature of the copper block is controlled by a conduction heat leak to the dewar. It is maintained at $-100°C$ with a stability better than $0.5°C$ by means of an electrical resistance heater wound around the copper block and monitored by a resistance sensor embedded in the copper block, and a servo amplifier loop regulation. The copper block is mounted rigidly onto the cryostat upper flange through thermal insulating nylon standoffs, allowing good alignment with the entrance window and the telescope optical axis. This also allows the CCDs to be mechanically decoupled from the cold finger (Fig.4).

A copper radiation shield with high quality mechanical polishing and covered with layers of super-insulating aluminized mylar surrounds the setup, ensuring a constant temperature. This shield consists in three parts : a bottom part, with a disk shape which is in contact with the upper copper head of the LN2 dewar ; a cylindrical part surrounding the mosaic with apertures in order to allow cabling routes, an upper disc with a central rectangular aperture which delimits the field of view. A rectangular copper polished shroud surrounds this aperture in order to avoid incoming stray light. The upper disc and the cylindrical shroud are screwed together. The bottom part is connected to the cylindrical shield through a row of commercial flexible copper-beryllium spring-strips ; this allows the possibility of disconnecting the two shields while maintaining good thermal contact. The same principle was used for the cold finger (see below).

The cryostat consists of two thermally insulated parts : a lower section acting as a dewar and a dismountable upper section containing the CCDs and their associated wiring. Thermal contact between them is ensured via a copper plate cold finger connected with a socket to beryllium-copper flat spring-strips.

The dewar is shown in Fig.4. It has a liquid nitrogen capacity of 6 liters providing a stability hold time of 10 hours. Outer thermal insulation was realized by a classical double shell dewar providing a vacuum space filled by super-insulating aluminized mylar layers, and an active charcoal layer maintaining steady clean vacuum conditions. This last requirement was necessary as the CCDs operate in the same vacuum as that of the dewar, and so need a very clean gas free entrance area. The top of the dewar is a high purity copper plate connected to the dismountable cold finger ensuring cooling of the CCDs copper block. Due to the very low thermal conductivity of stainless steel, it was necessary to weld on the top copper plate a large copper rod inside the dewar. This keeps the dewar top surface at the temperature of liquid nitrogen in upward-looking positions. The inner LN2 filling tube extends from the middle to the top of the stainless steel container allowing arbitrary orientations of the cryostat. This tube acts also as an exhaust for evaporated nitrogen.

Two metal boxes containing the CCD electronic control are mounted on opposite sides of the cryostat as indicated in fig.4.

A special high purity silica glass curved window, which is an active element of the secondary optics, closes the cryostat.

6 Camera facility equipment

6.1 Front end rack

The power drivers and first level monitoring equipment are grouped in a rack located in the dome. This limits signal cables to lengths of 15 m. The signals from this rack are then relayed to the control room which is located 25 m away. This dome installation contains the power supplies, the regulators, the protocol interface between VME bus and line drivers. It contains also the temperature readouts, window thermal regulation, thrusts control cards and filter motor control card.

A general control crate ensures the general main powering and start-up, the electrical protection of power supplies, and the connections general network. A regulation crate ensures control and monitoring of the apparatus as described in the following subsections

6.2 CCD thermal regulation

The servo amplifier loop regulator operates in the current mode according to a PID feedback protocol (proportional-integral-derivative). According to the information given by one of the two temperature platinum sensors embedded in the copper block, it delivers a modulated current to the electrical resistance heater, which consists of two turns of platinum wire, glued with epoxyde around the copper block, allowing good thermal contact. In order to avoid stray signals caused by electromagnetic perturbations on these loops, each half of the two turns are wound in opposite directions. The two connected identical temperature probes provide redundancy, ensuring good reliability of the measurement.

6.3 Window thermal regulation

Because of its vicinity to the cold thermal copper shield, the cryostat entrance window needs to be heated above the dew point in order to avoid surface water condensation which would result in light absorption and dispersion, degrading the image quality.

The temperature of the window is monitored by another PID amplifier loop regulator, controlled by a platinum temperature sensor glued in a hole directly drilled in the flange which supports the window. This regulator controls the current output of an NPN transistor which acts as a power stage.

6.4 Temperature probes

Apart from the regulation probes, other temperature measurements are taken into account. These temperature sensors are platinum resistors with 100 Ω resistivity at room temperature (PT100). They are all connected to analogical converters delivering a signal in the range 0-10 V to the data VME bus. They continuously monitor the temperature of the copper block, the temperature of the radiation shield (2 sensors), the high level (cryostat full) for the automatic liquid nitrogen refilling, and the temperature of the telescope.

6.5 Motorizations

The camera is equipped with computer controlled motors operating the shutter, the filter-carrier and three independent drive focal-screws fitted in the front part of the cryostat. These motorised systems are electrically off during exposures to avoid any stray signal that could disturb CCD reading, and thermal perturbation which would result in convection in the air above the telescope, causing optical index gradients.

6.5.1 Shutter

The shutter must close the optical window very quickly with a constant illumination for short exposures (0.1 second to close a 29 x 78 mm^2 window). On the other hand the shutter has to remain open from a few seconds for flatfields to about half an hour for normal operation. The shutter is driven with a stepper accelerated, from 0 to 0.35 $m.s^{-1}$ along 8 mm outside the field of view, equivalent to a rise time of 0.05 second, in order to have a constant speed across the aperture window. The closure begins on the side which has first been lit, which ensures a constant illumination of the sensitive area. An exposure time as short as 1 second is reproducible at the level of 1.7% r.m.s.

The shutter motor is driven by a commercial multi-axis driver card. This stepper motor translator card was chosen for its "Europe" standard possibilities : its control digital inputs/outputs provided by an angle coder, optical thrusts, mechanical zero sensor and external trigger, and so on. The power set of this card is protected against electrical network perturbations by galvanic insulators. During exposures, the shutter is maintained in the correct position by a mechanical brake. An electromagnet releases the clutch when the shutter is moved. This magnet is controlled from VME. Three optical thrusts control the shutter location.

6.5.2 Filter carrier

The filter carrier is moved with a direct current motor torque and is able to position its three filters with a reproducibility better than 50 μm. The motor moves the filter carrier through a reduction gear assembly. When the filter-carrier arrives in the right location, an optical thrust switches off the motor which is disengaged. Then an index roller gets in a slot of the filter-carrier. A spring maintains the roller pressed to lock the filter-carrier. The electronic driver is realised by a logical type card based on programmable logical network chips. Two functions are integrated in the card : the first controls positions of the filter carrier (rotation direction and stop) and the cut-off relay ; the second function provides the two bits coded position signal to the VME bus and to a view-meter consisting of three photo-diodes.

6.5.3 Focal screws

There are three focal screws driven by stepper motors to adjust the camera sensitive plane to the Cassegrain focal plane. A stiff structure was studied to avoid clearances and deformations so as to minimize small displacements of the camera. These three motors are associated with three incremental coding systems the signal of which is sent to the axis driver card that is identical to the shutter's. The received signal allows a closed loop regulation process.

6.5.4 Optical thrusts

The 15 optical thrusts consisting of infrared sensors are read by an analogic card. Good accuracy and reliability were the reasons for this choice. These sensors could be activated or disactivated by computer in order to avoid heat convection and infrared stray light. The dedicated readout card can be adapted to different functions through the mean of straps.

6.6 Line drivers

Because of the distance between the camera mounted on the telescope and the control room, the TTL signals are transmitted through two special driver cards which ensure compatibility between VME crate and the interface in the front-end rack. These cards use integrated differential RS422 driver circuits compatible with TTL signals. The inputs and outputs are also optically insulated thus reducing network conduction noise perturbations.

7 Current status and performance

As of March 1993, the camera has been operating for over 15 months. When the Large Magellanic Cloud is visible, more than 5 images per hour are taken on a 1.1×0.44 square degree area in the LMC bar. Flat-fields and offset images are taken every day, just before and after the observing period. About 12 000 pictures (flat-fields and LMC images) were successfully registered and stored during the periods December 91/April 92 and August 92/March 93.

The coplanarity of the different CCDs with respect to the mean image plane is better than ± 25 microns, which corresponds to a quarter of the focal field depth. The inter-chip pixel alignment distribution over the whole area has a precision of 9 microns r.m.s. This accuracy is in fact not needed for the microlensing search for which each star image is located on a single CCD.

The bandwidths of the blue and red filters have been chosen so as to transmit the maximum flux while having a large separation between the mean wavelengths, but still with a good average quantum efficiency of the CCDs. These two filters do not correspond to photometric standards. The third filter is a V Bessel filter. Fig.5 gives the transmission curves of the three filters used. The accurate positioning of the filter for each picture allows to eliminate the filter defects after flat-field corrections.

During the first period of observation, the spots of the stars appeared elongated on the images. The reason was a differential mechanical flexure between the 40 cm telescope and the small telescope which ensures the guiding. An improvement of the mechanical assembly structure after the first period of observation reduced the image displacement to 150 μm from the first to the last picture during a full night which corresponds to an elongation of 5 μm on a star image of 40 μm diameter recorded during 8 minutes exposure time.

It was also observed that the focus had to be adjusted twice a night, mainly due to the temperature variation inside the dome. The temperature of the telescope aluminum tube is now recorded and used to compute the estimated focal plane position from the varying separation between primary and secondary mirrors of the thelescope. The quality of the focus on the CCD array is continuously checked by means of star image elongations – induced by residual astigmatism – which rotate by 90^o from infra to extrafocal positions. The orientation of the elliptic image allows to know the sign of the focal plane correction to be applied. The amount of the correction is given by the temperature-mirror separation relation.

The measurement of the differential focus across the mosaic area allows one to adjust the orthogonality of the mosaic with respect to the optical axis of the telescope to an accuracy of better than 0.5 mrad.

8 Conclusion

Using a 400 x 579 buttable CCD developed by Thomson-CTS, a 20 cm^2 sensitive area camera has been built. Associated with a 40 cm dedicated telescope, it has allowed to record more than 10^5 stars per picture on the Large Magellanic Cloud, at a rate of 5 exposures per hour.

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Figure Captions

Figure 1 - Schematic overview of the instrumental system.

Figure 2 - A view one the edge-buttable CCD THX 31157, together with the 2x8 CCDs mosaic assembled.

Figure 3 - Mechanical mounting of the CCDs array on the cold copper plate.

Figure 4 - General layout of the CCDs camera.

Figure 5 - Transmission of the three filters used. The filters were built at the Laboratoire d'Astronomie Spatiale (LAS) in Marseille.

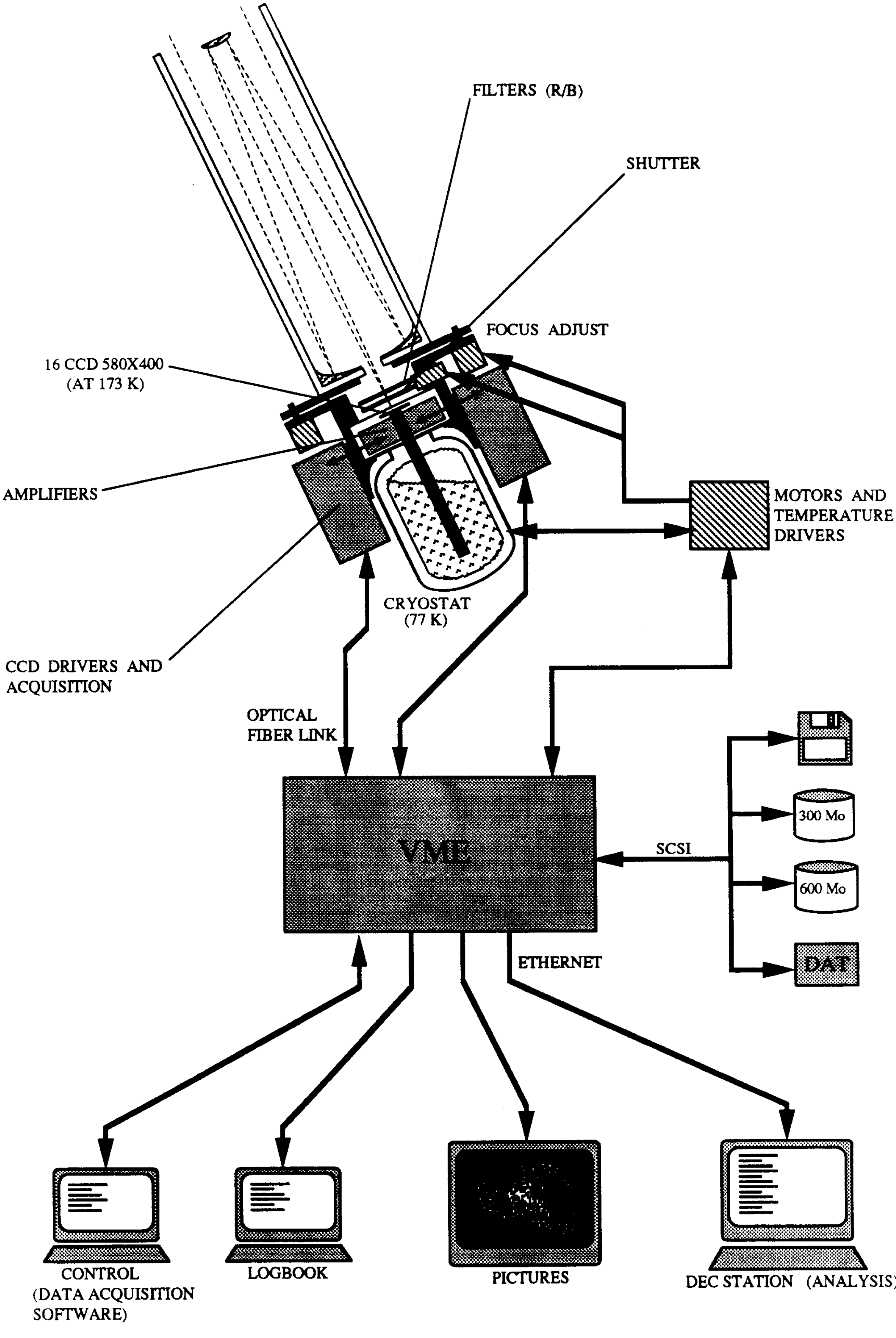

FILTERS (R/B)
SHUTTER
FOCUS ADJUST
16 CCD 580X400
(AT 173 K)
AMPLIFIERS
MOTORS AND
TEMPERATURE
DRIVERS
CRYOSTAT
(77 K)
CCD DRIVERS AND
ACQUISITION
OPTICAL
FIBER LINK
VME
SCSI
300 Mo
600 Mo
DAT
ETHERNET
CONTROL
(DATA ACQUISITION
SOFTWARE)
LOGBOOK
PICTURES
DEC STATION (ANALYSIS)

Fig. 1

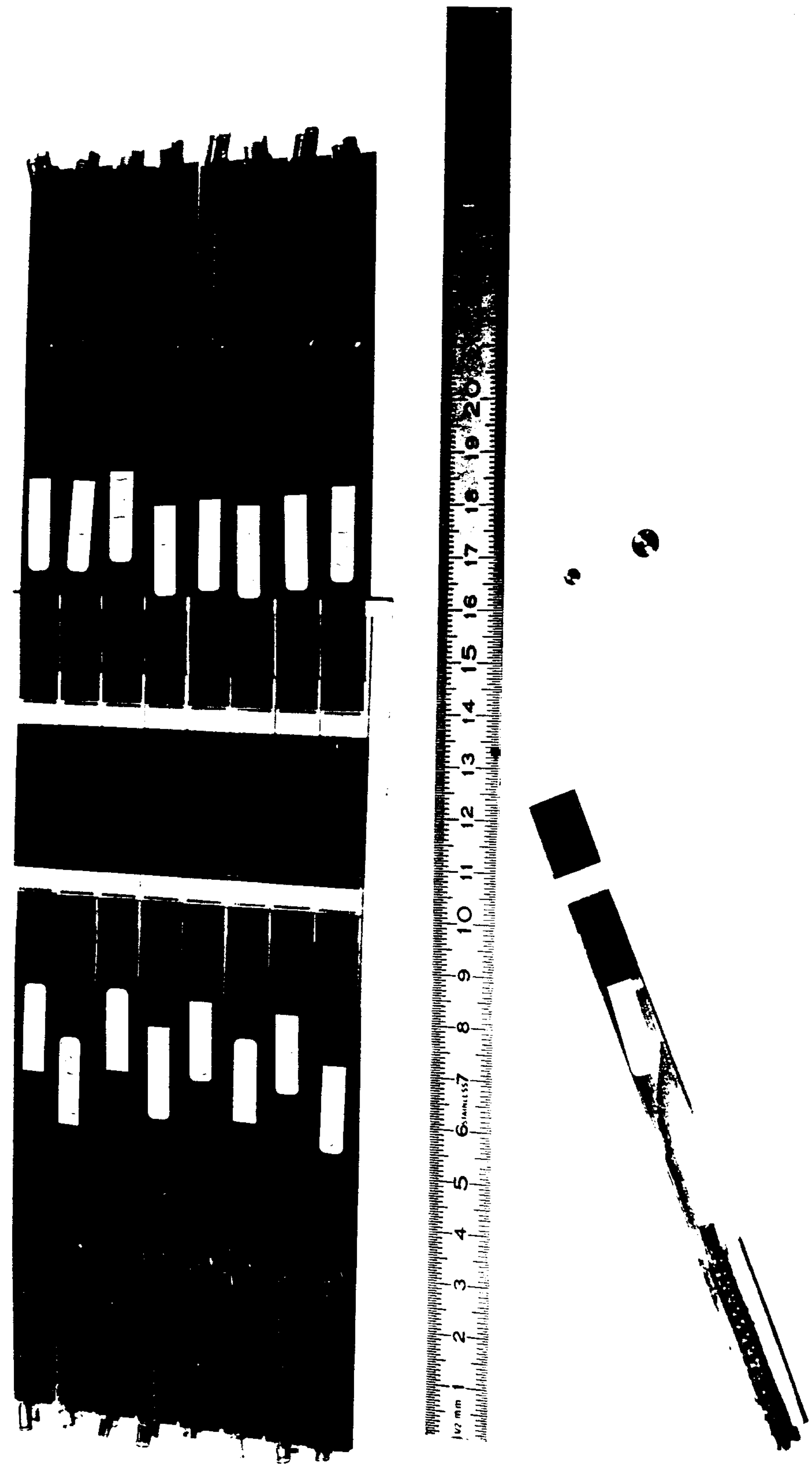


Fig. 2

CCD array

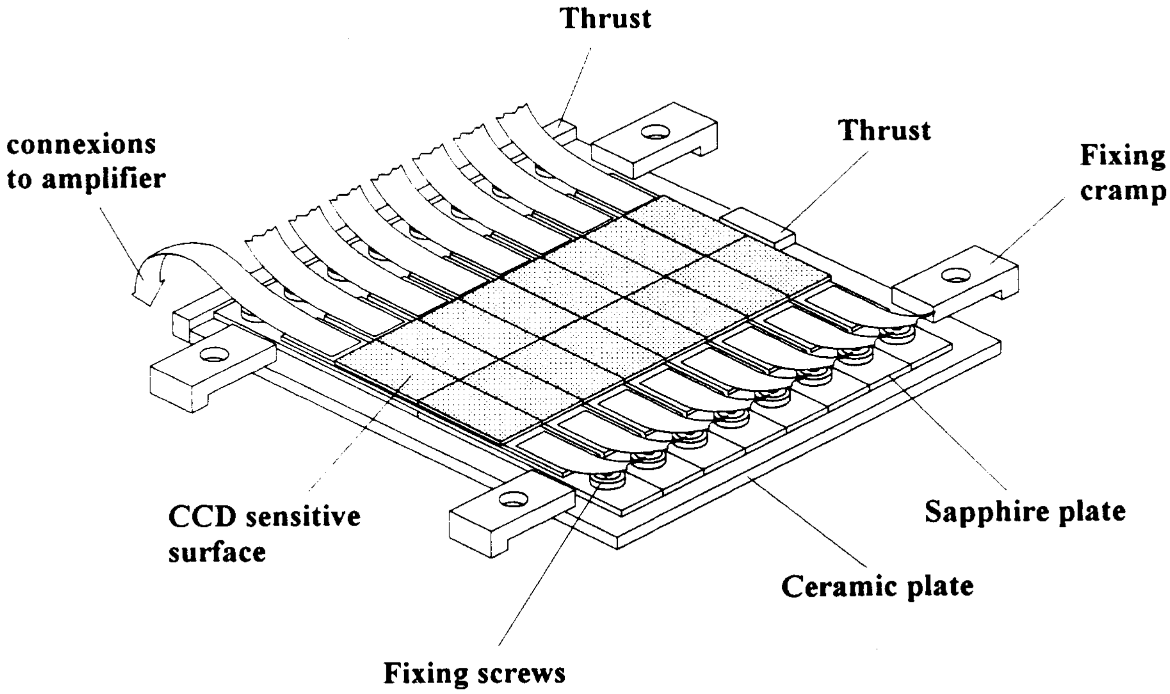
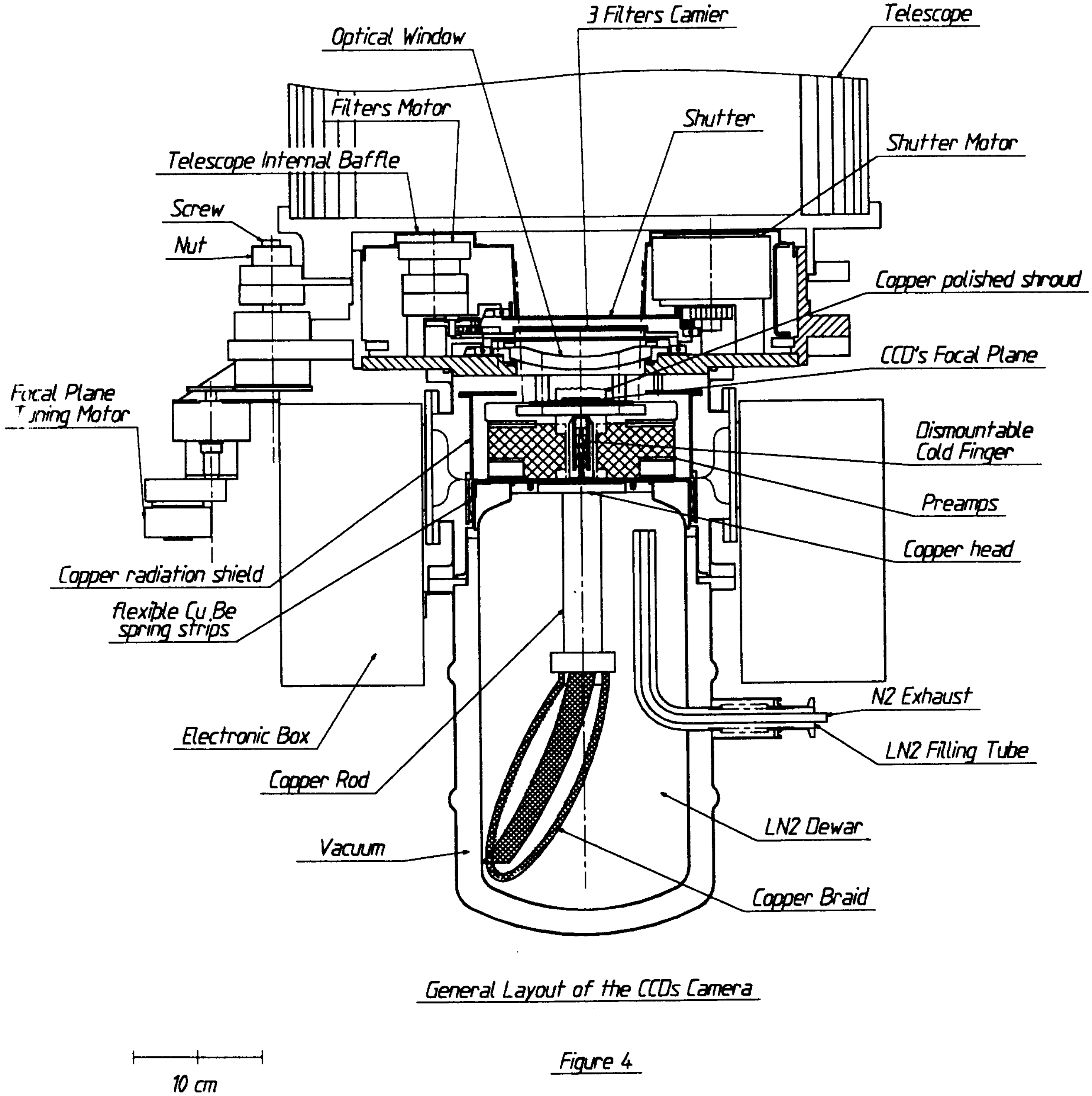
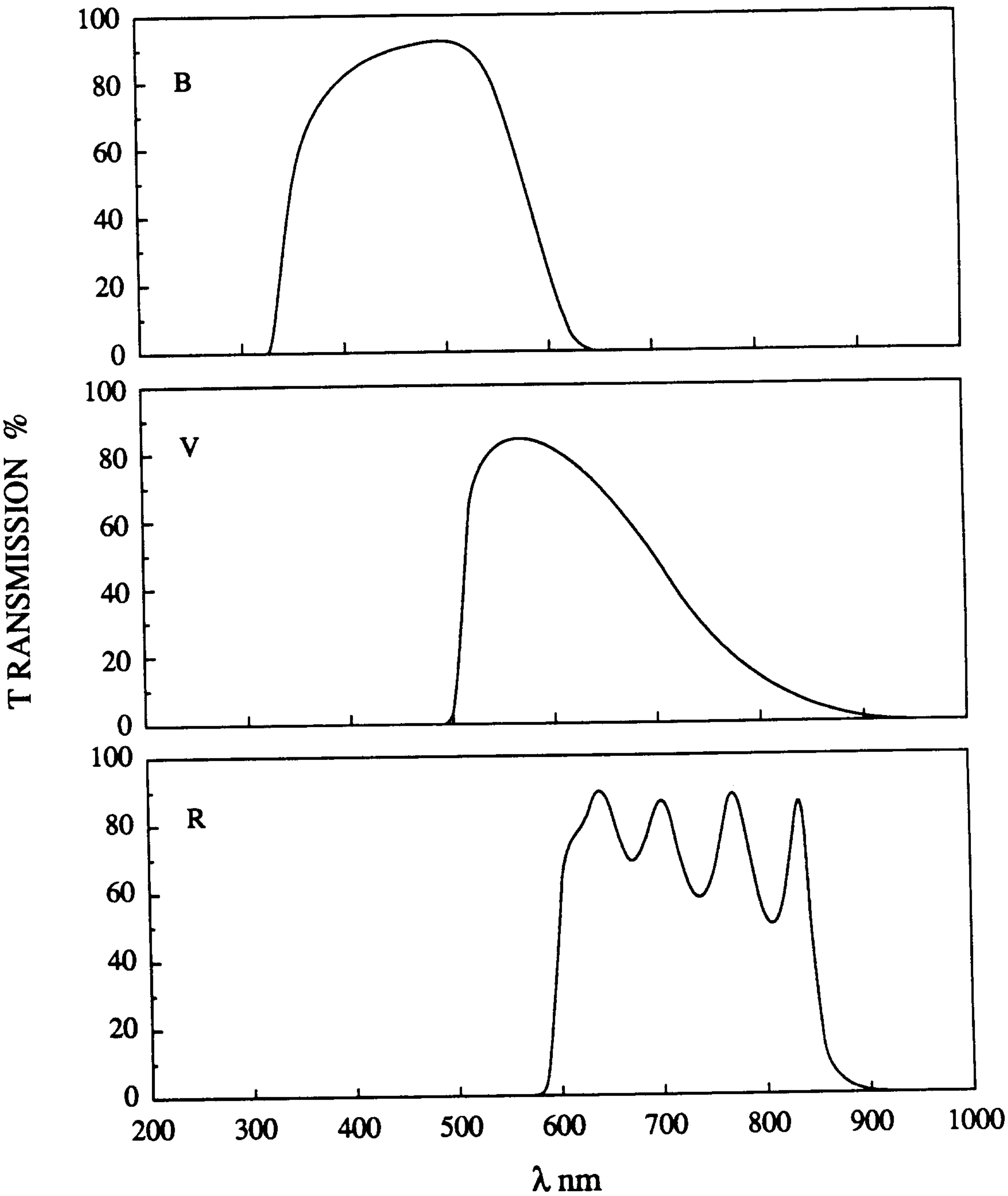


Fig. 3



General Layout of the CCDs Camera

Figure 4



B
V
R
TRANSMISSION %
0
20
40
60
80
100
200
300
400
500
600
700
800
900
1000
λ nm

Fig. 5