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CCD camera and automatic data reduction pipeline for the Mercator telescope on La Palma

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ABSTRACT

In this paper we present the development of a CCD imager for the modern 1.2m MERCATOR telescope dedicated to long term monitoring of variable astrophysical phenomena. This instrument is a result of the collaboration of the Observatory of Geneva with the Institute of Astronomy in Leuven. After a technical description of the main components of the CCD camera system, the text will focus on the automatization of the observations and subsequent data reduction. The telescope itself is an altazimuth mounted 1.2 m Ritchey-Chretien telescope and is operated in a semi-automatic mode. The system executes a predefined sequence of observations, that only need occasional checking of data quality by the astronomer. The observation software is written in a FORTRAN based interpreter language (INTER) running on a UNIX system that communicates with the astronomer via GUIs implemented in Perl/Tk. The data reduction is integrated into one package and includes pre-reduction, photometric and astrometric calibration, extraction, catalogue preparation and archiving. This allows to have a GUI driven reduction that is both flexible and robust. The preliminary reduced data give the astronomers an indication of the quality of their observations, so that they can adjust their program or camera settings during the same night.

Keywords: CCD photometry, data reduction pipeline, optical astronomy, instrument design, automated observing

1. INTRODUCTION

The Mercator Telescope was built after the Ritchey-Chretien design and has a 1.2 m primary mirror and a total focal length of 14.4 m. It has an altazimuth mounting and disposes of two focal stations (Nasmyth and Cassegrain) with a usable field of view of 20 arcmin (80 % of encircled energy within 0.3" at 633 nm). When it went into operation in 2001 at the Roque de los Muchachos Observatory on La Palma, it was equipped at the Nasmyth focus with a photo-electric two channel photometer (P7-2000)[1] using the Geneva photometric system. For the remaining focal station the aim has been to develop a CCD imager that will be called MEROPE (**MER**cator **O**ptical **P**hotometric Imag**E**r), using filters going from U to I. The mounting being an altazimuthal one, there was also a need to construct a field derotator. An important aspect of the complete observatory system is that it has to be possible to be operated by a small local staff. This adds complexity but this can be supported by personnel at the home institutions. In the next sections we will describe following aspects of this new instrument: science drivers, system layout, mechanical parts, optical parts, detectors, operations, software implications (control and observations) and data reduction strategy.

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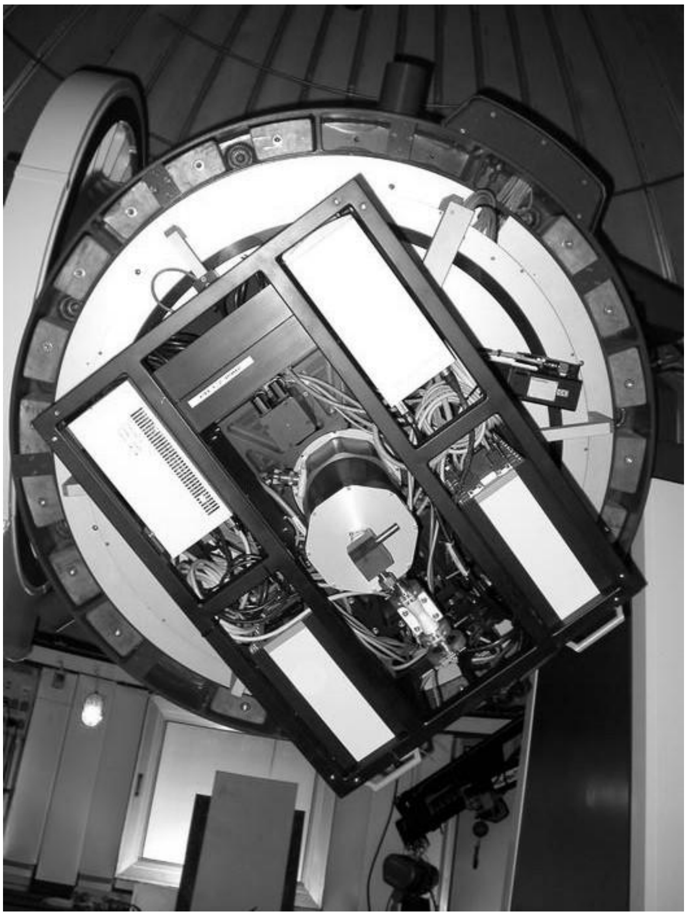

Figure 1. The CCD imager on Euler's (Mercator's twin telescope on La Silla Observatory) Cassegrain focal plane

2. SCIENTIFIC DRIVER

In the last decade, the European Southern Observatory (ESO) and all other large observatories worldwide focused on the construction of telescopes with large entrance apertures. This, together with the progress in detector technology, image analysis, mirror correction (active) and seeing correction (adaptive) optics, opened new frontiers in the ground based observational investigation of faint objects. Moreover, we are at the verge of a new era where combined foci of several large telescopes will yield unprecedented high angular resolution information of celestial objects.

The drawback is that, in international observatories, it became increasingly difficult to embark in monitoring programs. The construction of modern, highly efficient dedicated smaller telescopes by individual countries and/or institutes is therefore necessary and very complementary to the large projects too big for individual countries to pursue. The study of time-series is, by all means, still very important not only in stellar astrophysics but also in objects like Active Galactic Nuclei, Gravitational Lenses etc. A flexibly operated telescope allows also an easy and rapid response mode for bright Gamma Ray Bursts, SNe etc. The MERCATOR telescope combined with an efficient instrument park which is maintenance friendly fits, therefore, in the specific niche and allows for efficient observational studies of time-series of variable phenomena. A CCD camera is a natural component of the instrument package and in this contribution we describe the whole project, from design to the data reduction and archiving streamline, of the CCD camera for the MERCATOR telescope.

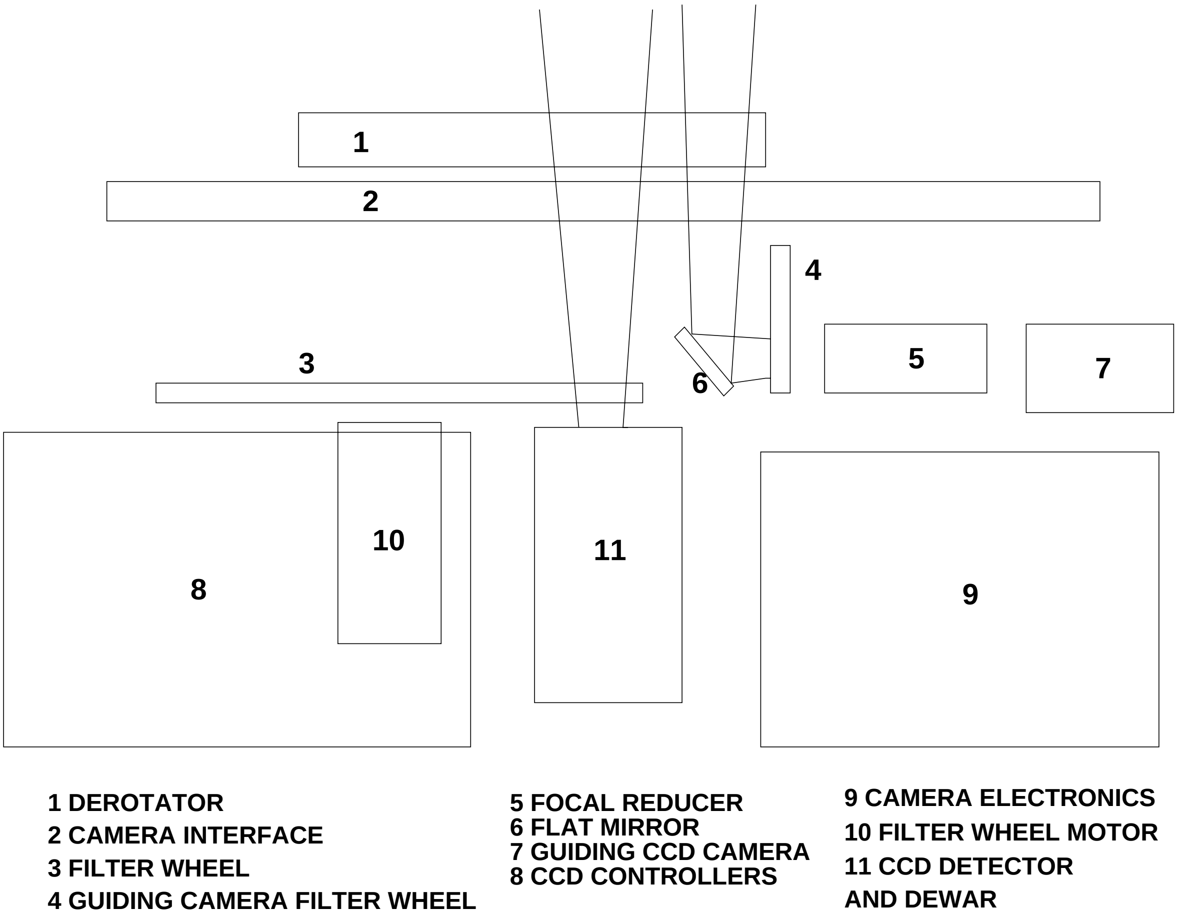

Figure 2. Schematic layout of the CCD Imager MEROPE on Mercator's Cassegrain focal plane

3. SYSTEM LAYOUT

The CCD imager has the following main parts: an instrument adapter/field derotator, cable wrap, a filter wheel, an autoguider unit, the detector head and cryogenic dewar, driver electronics and on board computer. The chosen CCD detector is a back-illuminated thinned device having 2Kx2K 13.5 micron size pixels yielding a scale of 0.193 arcsec/pixel and a field of 6.6 x 6.6 arcmin^2 since there are no mirror nor lenses in the imager, except in the autoguider beam. The filters cover the entire spectral range where the detector is sensitive and were calculated to mimic the Geneva photoelectric system between filters U and V. At longer wavelengths Gunn was chosen for R and Cousins for I.

A picture of the instrument can be seen in Fig. 1 and a schematic view in Fig. 2.

The field derotator had to be kept as flat as possible because the back focal distance is quite small (70 cm). A compact instrument also minimizes flexure. The off axis autoguider does not interfere with the beam intended for the science chip, in order not to waste any photon for the relatively small telescope. The average distance from the axis of the guiding star is 10 arcmin. The autoguider has its own filter wheel with 4 positions (red, blue, transparent and green) in order to reduce differential (for colour or zenithal distance) atmospheric refraction. The main filter wheel has 16 positions which are filled with the 7 Geneva filters (U, B, B1, B2, V, V1, G), R, I, transparent, and a special U filter that combined with the Geneva U filter generates a passband completely on the blue side of the Balmer discontinuity. The on board computer was chosen to minimize the number of cables that have to pass through the cable wrap. The computer acts as a local control unit for the

Table 1. Main technical data of the Mercator CCD Imager MEROPE

weight	150 kg
overall dimensions	68.5 cm x 64 cm x 98 cm
number of pixels	2048 x 2048
field size	396.1 x 396.1 arcsec^2
pixel size	0.19 arcsec/pixel
quantum efficiency	80% @400 nm, 90% @500 nm, 85% @600nm, 75% @700 nm, 55% @800 nm, 30% @900 nm
readout noise	3 electrons RMS @25KHz pixel readout rate
dynamical range	16 bit ADC
filters	50 mm diameter, 16 positions
filter set	Geneva U, B, B1, B2, V, V1, G, Gunn R, Cousins I
autoguider filters	40 mm diameter, 4 positions, B, V, R, transparent BK7
autoguider resolution	0.56 arcsec/pixel
autoguider field size	576 x 876 arcsec^2 @700 arcsec off-axis and vignetted outside the center square 576 arcsec region

CCD detector controllers. The temperature of the filters need to be controlled since their passbands shift when the temperature changes. To achieve this they are heated with resistances if the temperature falls below 25 C. Auxiliary equipment needed for the operation of the camera but not mounted on the telescope structure are: vacuum pump for the dewar and a liquid nitrogen reservoir and filling system. The interface for the user runs on the workstation in the control room, which is 30 m distant from the dome. In Table 1 the main characteristics of the camera are summarized.

In the following two sections we will discuss the mechanical and optical parts of the CCD camera.

4. MECHANICAL SUBSYSTEMS

The CCD camera will be installed at the Cassegrain focal plane behind a field derotator. This field derotator is necessary to track the celestial objects over the entire field of view, to use a field orientation of your choice or to select an appropriate guiding star. The filter wheel used in the camera has 16 positions for 50 mm diameter filters and is driven by an on axis servo motor and a safety coupling. Accurate positioning (0.1 mm) is achieved by an index and notch mechanism. This precision is needed because the filters are not fully homogeneous. Furthermore, the temperature of the filters has an effect on the central wavelength of the transmission band. So temperature control of the filter environment has been taken into account by using resistance heating and active heat convection by ventilators. The next subsystem is the autoguider unit that consists of a deviating flat mirror, a filter wheel, a focal reducer, an objective and a Peltier cooled CCD camera. The 56 mm by 42 mm flat mirror takes a 9.6 x 9.6 arcmin^2 field centered at 11.5 arcmin from the optical axis. The autoguider filter wheel has four 40 mm filters to minimize the differential atmospheric refraction (colour dependance) between the science field and the guiding star. The focal reducer (FR) (4.3X) was necessary because the autoguider CCD chip is quite small (2.2x3.3 arcmin^2 without FR), thus increasing our chances to find a suitable guiding star. Finally, a commercially obtainable objective forms an image on the CCD sensor. The focusing of this autoguider unit is done on sky during commissioning by moving both the FR and the autoguider camera head and objective with respect to each other, not requiring any further interactions.

5. OPTICAL COMPONENTS

The most important optical components of the CCD imager are the filters, their function being to let pass only a selected part of the received radiation and not to deteriorate the image quality offered by the telescope. The filters were carefully calculated by one of the co-authors (dr. Fabien Carrier) to mimic the Geneva photo-electric

Table 2. Characteristics of MEROPE's filter set

Filter name	Central wavelength (nm)	Passband (nm)
U Geneva	340.7	315-365
B Geneva	419.6	375-463
B1 Geneva	398.4	376-411
B2 Geneva	446.4	425-464
V Geneva	546.4	505-574
V1 Geneva	538.2	508-560
G Geneva	577.8	550-590
R Gunn	664.1	610-715
I Cousins	759.8	710-810

photometry. The data used in these calculations were the CCD chip's quantum efficiency, the transmission curves and thicknesses of the constituent glasses that form the filter in both the photoelectric and CCD instrument, the responsivity of the photomultiplier and the spectral energy distribution of a whole set of reference stars. The free parameters in this exercise were the thicknesses of the coloured glasses and the choice of the kind of glass. Another condition we wanted to be met, was that all filters had to be parfocal (by adding Suprasil glass where necessary). In table 2, the central wavelengths and passband widths are given for the filters that will be used.

The autoguider unit consists of following optical parts: a 45 degrees flat feed mirror, a filter set, a focal reducer that consists itself of 2 doublets and a multi element objective. The optics were designed by D. Kohler (OHP-France) with in mind making use of commercially available parts. The filters of the autoguider are B, V, R and a transparent one for faint guiding stars. The collimator has a focal length of 108 mm and a diameter of 40 mm. The objective has a diameter of 30 mm and focal length of 25 mm.

6. DETECTORS

The camera uses 2 CCD detectors. The scientific CCD chip is a back illuminated thinned device of grade 1, optimized for a high quantum efficiency around 500-600 nm and is cooled via a liquid nitrogen dewar. This chip has 2048 x 2048 pixels of 13.5 microns squared. The second chip is a front illuminated Peltier cooled device. It has 1580 x 1028 pixels measuring 9 microns squared each and serves in the autoguider unit. The light enters via an off axis mirror through a filter and commercial imaging optics. The guiding star can be chosen in an annulus centered on the main science target by choosing the position angle of the derotator. The distance between the two chips on the sky cannot be changed, however, and is indicated in table 1. Both detectors are controlled by an Antares 4200 EG&G 16-bit controller from Pixcellent Ltd. connected to a dedicated PC running under Linux.

7. OPERATIONS

At the time of publication of this article, the described camera system is in it's commissioning phase, so it is still too early to present any results or checked performances of the system. Therefore, we will mention here some practical aspects of its use. The instrumentation plan of the Mercator telescope calls for a minimum of maintenance operations and in fact we work with fixed installed instruments with minimal manual intervention. The CCD camera however needs to be cooled with liquid nitrogen. For it's supply we use a 180 liter pressurized tank, situated 8m below the observing floor, that is filled from a mobile LN2 tank through the observatory's wall. Twice a day (morning and afternoon) the camera's dewar is connected via a flexible hose with this 180 l tank and filled.

8. CONTROL AND OBSERVATION SOFTWARE

Like already mentioned in the introduction, a key aspect of our observatory operational system is that it can be operated by a minimum of local staff. In our case, the (visiting) astronomer is technically supported by two engineers/instrument specialists in permanent residence in La Palma. Automatization is therefore maximized; the telescope and instrument automatically follow a predefined queue of observations, supervised by the visiting astronomer.[2] The queue is prepared off-line with the aid of software tools that were written specifically to generate a complete telescope and instrument configuration list that can be read by the telescope's scheduler. During the night, the data coming from the instrument are displayed and archived on disk. The flexibility in the observations is located in the scheduler, where one can easily remove, repeat or introduce observations and change instrumental settings. The scheduler is a Perl program with a Tk graphical user interface (GUI) specially written for this telescope. It accepts input from the astronomer and communicates with a synchronizing program that itself is connected to different programs, each of them controlling part of the observatory system (telescope, CCD camera, autoguider camera). The preparation of the observations is done by means of another GUI, that makes use of GSC/DSS sky charts to choose the object, field orientation and size, guiding star and filter sequence.

9. DATA REDUCTION STRATEGY

The expected data flow is around 1 GB per night, so an efficient data flow has to be foreseen. Another important factor is homogeneity of the reduced dataset, independent from the person who performs the reduction. It is common practice to consider the CCD data reduction in 3 steps. A first phase concerns the removal of the instrumental effects (bias, dark, flatfield and astrometric correction), which can be highly standardized and automatized. A second phase is then to treat the standard star fields to determine the zero-point and extinction coefficient. The last phase then will identify and extract individual objects on the science frame, and create a catalog with accurate positions, magnitudes, color indices and reliable errors of the science frames. Since the reduction strategy depends very much on the scientific program and the field source density, we will develop a reduction package for which the pre-reduction is performed automatically as well as the zero-point and extinction determination while the science catalog determination will be project and user dependent. Most software does exist already and our data reduction scheme will wrap the different codes together. A user friendly GUI enables the observer to change reduction parameters if the default values are not adequate for a given scientific program.

Following packages will be used to achieve the complete reduction:

- EIS-MVM: this software performs the removal of the instrumental effect (bias and dark subtraction, flatfielding, defringing) and does an astrometric fit. It is publicly available since the end of 2003.[3]
- SExtractor: this package extracts sources from the calibrated science frame, makes a catalogue with pixel positions and instrumental fluxes and does a classification of the type of objects.[4]
- custom software has to be written to translate these fluxes in magnitudes and the positions into celestial coordinates with the help of CCD photometric standard fields.

9.1. EIS-MVM

This CCD image (pre)reduction package was developed at ESO by the ESO Imaging Survey group to support the different CCD instruments at the ESO observatories in Chile. The fact that it supports different CCD instruments (via the use of a configuration file in XML format) captured our interest. The XML (Extended Markup Language) standard is similar to the better known HTML, but, like its name tells, it offers more capabilities, one of them is that data can be structured hierarchically. Our work consisted in making the individual pieces of software work with our data. Basically, we had to provide the necessary FITS[5] keywords in the header (FILTER, OBJECT, EXPTIME, JULIAN-DAY, CRVAL1, CRVAL2, CRPIX1, CRPIX2, INSTRUME), put the files in some data structure and write a configuration file that reflects the setup of our instrument and the way in which we want our prereduction to be executed. In the versions of EIS-MVM we started to use, there

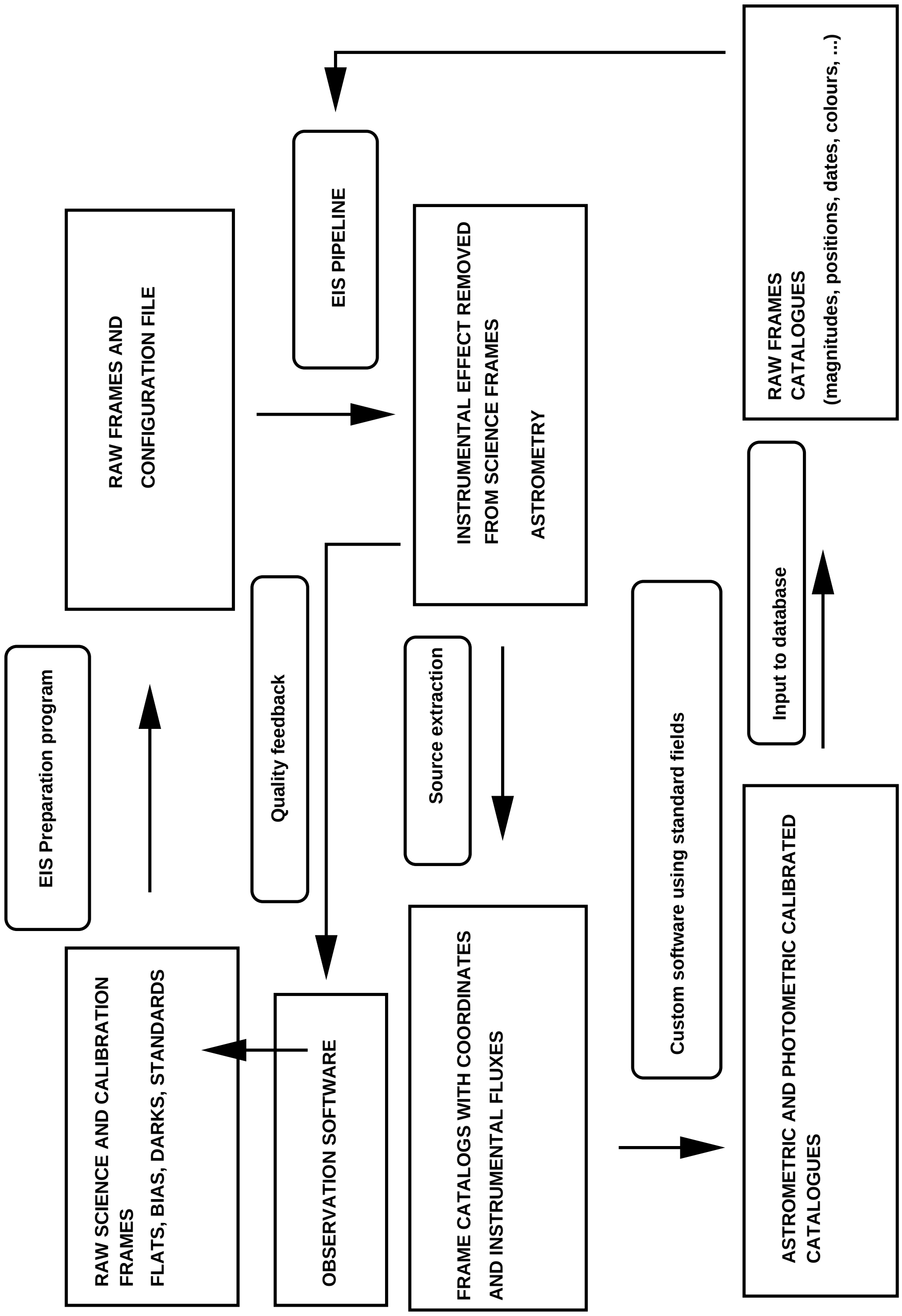

Figure 3. Data flow for the CCD imager, from the observations through the reduction process until the database

Table 3. Theoretical exposure times in seconds for UBVRI photometry with MEROPE on the Mercator telescope, S/N=300, b-v=0.5 for first half and 0.0 for second half

V magnitude	U	B	V	R	I
12	14	8	5	4	4
14	92	52	30	24	24
16	606	337	191	154	158
18	4817	2637	1382	1112	1141
12	9	5	5	4	4
14	58	32	30	24	24
16	375	209	191	154	158
18	2764	1523	1382	1112	1141

is a restriction concerning the orientation and size of the field, both have to be constant for a given instrument and have to be written in the configuration file. To bypass this condition, we wrote a C program that adapts this configuration file by getting the information from the FITS header keywords (via CFITSIO routines)[6] and then continues to use the standard EIS-MVM pipeline.

9.2. SExtractor

Once the instrumental effects are removed from the images, the next step is to locate the luminous sources in the field of the image. Since this is not done by the EIS package, another solution had to be found. A widely used software package among astronomers using CCD imaging is SExtractor developed by E. Bertin. It is capable to calculate positions in pixel coordinates and fluxes with error margins of luminous sources in the image. On top of that shape and size parameters are calculated that can be used to perform a classification into stellar or nonstellar objects. A basic photometric and astrometric catalog is the result of this step. The quality however is not optimal and can be improved by using custom made routines that use the SExtractor source detections to make a full photometric and astrometric calibration.

9.3. Photometric calibration software

We connected our own photometric calibration software (in FORTRAN) with the 2 external packages into one pipeline and provided a graphical user interface to visualize the settings and to show the progress and results of the data reduction. By observing standard photometric fields, we calculate the instrumental zero points for each band and the extinction and colour coefficients.

9.4. Database

The final products as well as the raw data then go into a database that can be queried via a MySQL software. This database also contains data obtained with the photoelectric photometer on the same telescope and spectroscopic data obtained with a similar telescope on La Silla Observatory (CORALIE on the Swiss Euler Telescope). Data obtained with the future fibrefed spectrograph HERMES[7] will populate the database. At the Institute of Astronomy of the K.U.Leuven the database is filled not only with CCD images and reduction results, but also with all data obtained by the staff of the institute. The query of a given object or position on the sky will generate all datasets available in the institute.

10. PERFORMANCE

We will illustrate the performance of the CCD imager on the Mercator telescope by giving some examples obtained with the use of it's exposure time calculator in table 3.

11. PROJECT PLANNING

The CCD imager is planned to be commissioned on La Palma during June 2004. This implies also the observational software (both operation of the CCD camera and the observations preparation tools). The data prereduction step should be available soon afterwards (July or August 2004). The final step of the data reduction pipeline will likely only be run at the home institute, because it requires too much attention of the astronomer. This will be implemented after the summer of 2004, when we will have obtained raw data for different types of research programs. It is, however, the intention to give feedback to the observer during the night about the data quality checked during the prereduction step.

12. CONCLUSIONS

In this paper we presented the opto-mechanical details of the CCD camera system that was built for the Mercator telescope. Further on, we discussed also the observational software, the CCD data reduction strategy and how they are linked. We make use of existing software packages that are modified slightly or complemented in order to fit with our requirements. Since the data are going to be injected into a database, the reduction has to be standardized and traceable. These aspects are fully supported by the chosen software. On the other hand, it has to be always possible to repeat the reduction process with a different set of parameters; this flexibility is also present in the custom written Perl/Tk GUI connected to the reduction pipeline. Finally, the feedback about the frame quality in near real time is a very useful feature for the observer.

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