OmegaCAM: Wide-field imaging with fine spatial resolution

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ABSTRACT

OmegaCAM is the wide-field camera for the VLT Survey Telescope being completed for ESO's Paranal observatory. The instrument, as well as the telescope, have been designed for very good, natural seeing-limited image quality over a 1 degree field. At the heart of the project are a square-foot photometric shutter, a 12-filter storage/exchange mechanism, a 16k x 16k CCD detector mosaic, and plenty of software for instrument control and data handling, analysis and archiving.

VST/OmegaCAM should come into operation in 2005. The design of the instrument (optical, mechanical, software), the current status and plans for its operation will be presented.

Keywords: imager, wide-field system, survey system, VLT/VST

1. INTRODUCTION

The availability of large-format CCDs and of computers able to digest huge data volumes, make it possible to conduct very large digital astronomical imaging surveys. Prime examples are the Sloan Digital Sky Survey[1], and the CFH Legacy Survey[2]. Conducting such surveys requires a large-format detector mosaic. In the era of 10m-class telescopes these large surveys can provide the primary material that the photographic sky surveys so successfully represented for the 4m-telescopes.

On Paranal Observatory in Chile, ESO's 2.6-m VLT Survey Telescope[3] (VST) will start operations in 2005. It is of modified Ritchey-Crétien design specifically designed for wide-field imaging, and has been optimized for excellent image quality in natural seeing. Thus, it will have active primary and secondary mirrors, a retractable atmospheric dispersion corrector, a constant focal plane scale of 0.21arcsec per 15μ pixel over a 1.4 degree diameter field, and a theoretical PSF with 80% of its energy in a 2×2 pixel area over the whole field. OmegaCAM is the wide-field optical camera for this telescope. It will be the sole instrument on the telescope, and will be mounted at the Cassegrain focus.

OmegaCAM is a huge optical CCD imaging camera: its 16k x 16k CCD pixels cover the square degree field of view of the VST almost entirely. The primary function of the VST and its instrument is to provide surveys in support of VLT science, be it in the form of large homogeneous multi-colour imaging surveys which form the basis for large-scale spectroscopic follow-up work, or in its ability to find rare or extreme astronomical objects for further study.

The designs of both VST and OmegaCAM try to take full advantage of natural good seeing, so it should also be a superb instrument for weak gravitational lensing surveys, or for monitoring projects designed to detect microlensing or supernovae. In fact, applications are manifold: one has only to look at the exciting science that is now coming out of the Sloan Digitized Sky Survey to realize the potential of VST/OmegaCAM, which has a comparable field of view to the SDSS camera, but will operate continuously, with better image quality and higher throughput.

The scale of the instrument means that once operations start the challenge is not at all over: OmegaCAM will generate of order 50GByte of raw data per night, year after year, and such a volume of data can only be digested by means of a strict observing protocol combined with highly automated processing of the data.

In this article, we present the basic features and design of the instrument.

2. OVERVIEW OF THE INSTRUMENT

2.1. Detector system

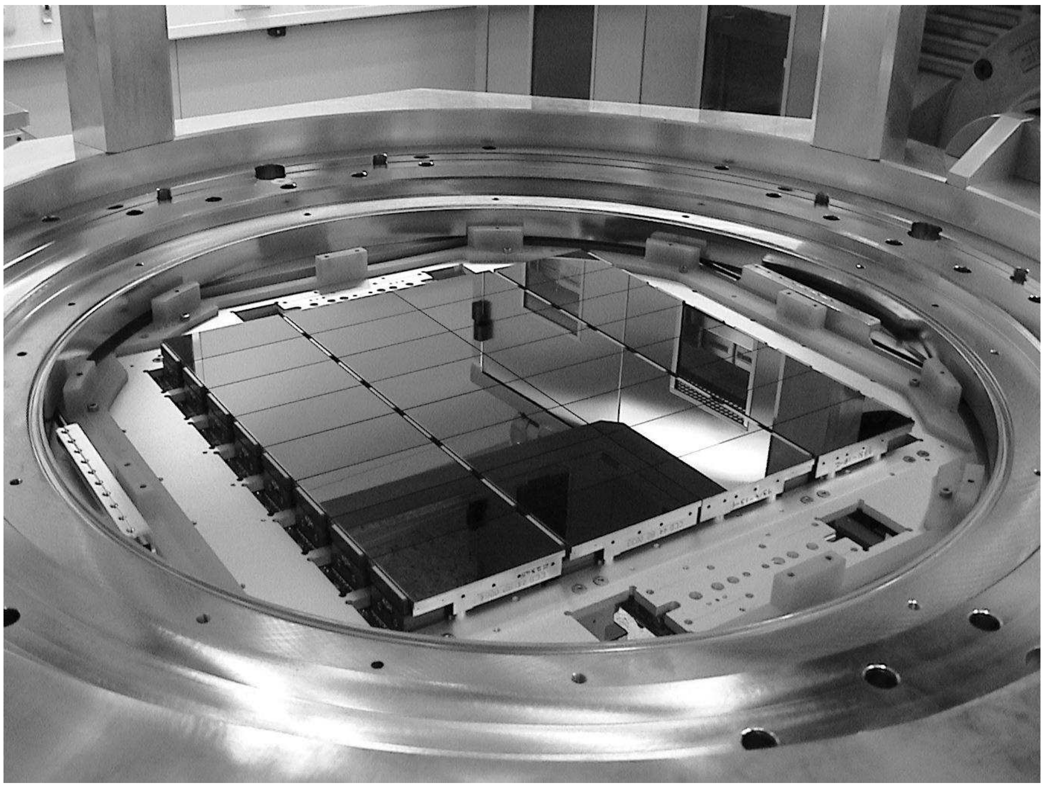

Figure 1. *The OmegaCAM focal plane in the laboratory, populated with dummy CCDs. This arrangement minimizes the amount of dead space between devices, given the constraints imposed by connecting the read-out ports. In the VST the array covers a 1x1 degree area. In addition to the 32 CCDs shown here, in the periphery the mounting holes can be seen for the four auxiliary detectors—two of these are for autoguiding, and the other two for image analysis.*

The heart of OmegaCAM is the CCD mosaic (Fig. 1), being built at ESO headquarters in Garching. It consists of a 'science array' of 32 thinned, low-noise ($5e^-$) 3-edge buttable 2x4k Marconi (now E2V) 44-82 devices, for a total area of 16384 x 16384 15μm pixels (26x26cm!). The science array fits snugly into the fully corrected field of view in the focal plane of the VST, and covers an area of 1x1 degree at 0.21 arcsec/pixel. Around this science array lie four 'auxiliary CCDs', of the same format. Two of these are used for auto-guiding (on opposite sides of the field: the field is so large that also field rotation will be auto-guided), and the other two for on-line image analysis. For this purpose the latter CCDs are deliberately mounted out of focus (one 2mm in front, one 2mm behind the focal plane), and the resulting defocused images can be analyzed on-line and used to infer aberration coefficients such as defocus, coma, or astigmatism every minute. The whole detector system is

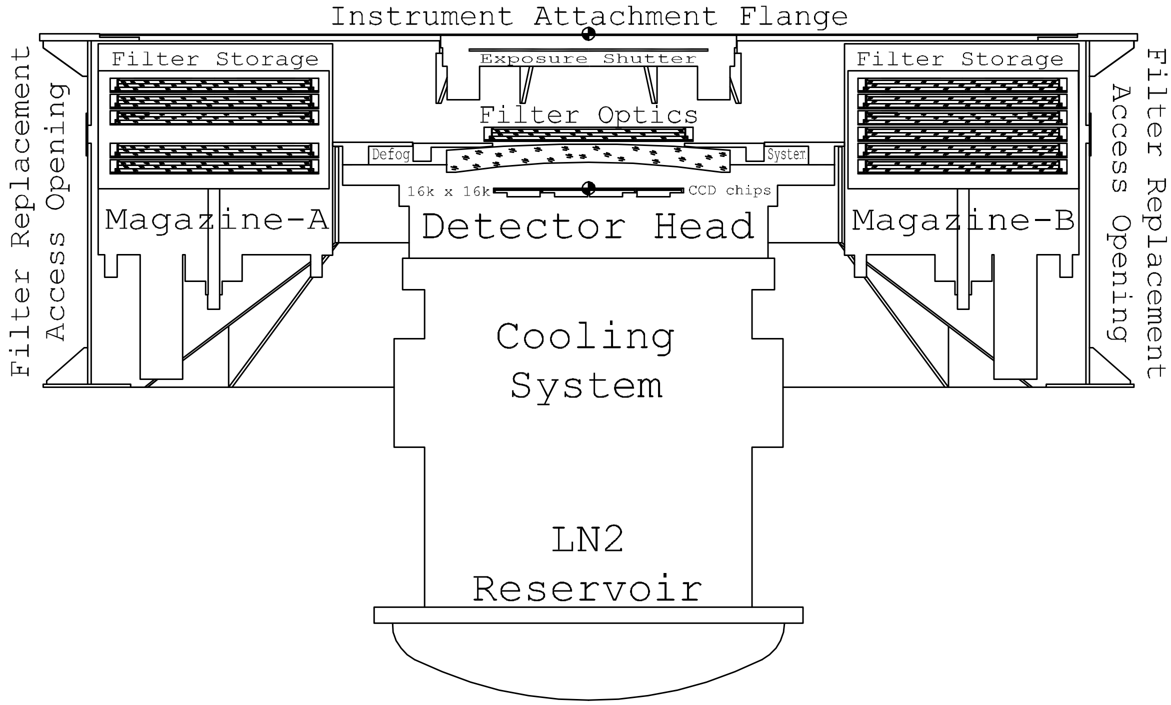

Figure 2. *Schematic view of the instrument. Key components are labeled*

mounted behind a large, curved dewar window (the final optical element in the VST design) and is cooled using a 40-l Nitrogen cryostat. Readout of the full mosaic takes 45s, and is accomplished by two FIERA controllers (a third FIERA takes care of the four guiding and image analysis CCDs).

2.2. Hardware

In front of the dewar window is the mechanical part of OmegaCAM[4]: closest to the CCD window sits the filter exchange mechanism, and above that the shutter. The housing provides the mechanical link between the telescope flange and the detector/cryostat system.

Figure 2 gives a section view of the final design that foresees a cylindrical housing with a spoke-like rib structure to support the axisymmetrical loads at the Cassegrain focus. The real housing with integrated shutter and magazines can be seen in Fig. 3.

The filters are stored in two magazines which can move up and down, either side of the focal plane, through large shafts in the housing. A linear stage slides filters into the beam, where they are locked into place by means of movable notches. The total number of motors used in the filter exchange and positioning mechanism is 7. High precision filter positioning ensures that intensity variations in the flat fields due to optical imperfections in the filters (dust grains, etc) are less than 0.1%. The filter exchange unit is built in such a way that it allows one filter to be pulled into the beam while the previous one is pushed out, allowing efficient observing in spite of the rather large distance the filters have to travel. Filter exchange time depends on how far the magazines need to move and whether the incoming and outgoing filter belong to the same magazine or not. Provisions for increasing the efficiency of observations are made in software (see section 2.4) and planned for instrument operations (optimized distribution of filter in magazines).

The filters are large and heavy: when fully loaded with 12 filters, the instrument will contain 40 kg of filter glass alone! During the filter exchange process about 17kg are moved (mass of 2 filters and the carriage).

The exposure shutter[5] is one of the key units of OmegaCAM (Figure 4). It consists of two carbon fiber blades which open and close the light path. They are driven by 2 micro-stepper motors and move smoothly on linear

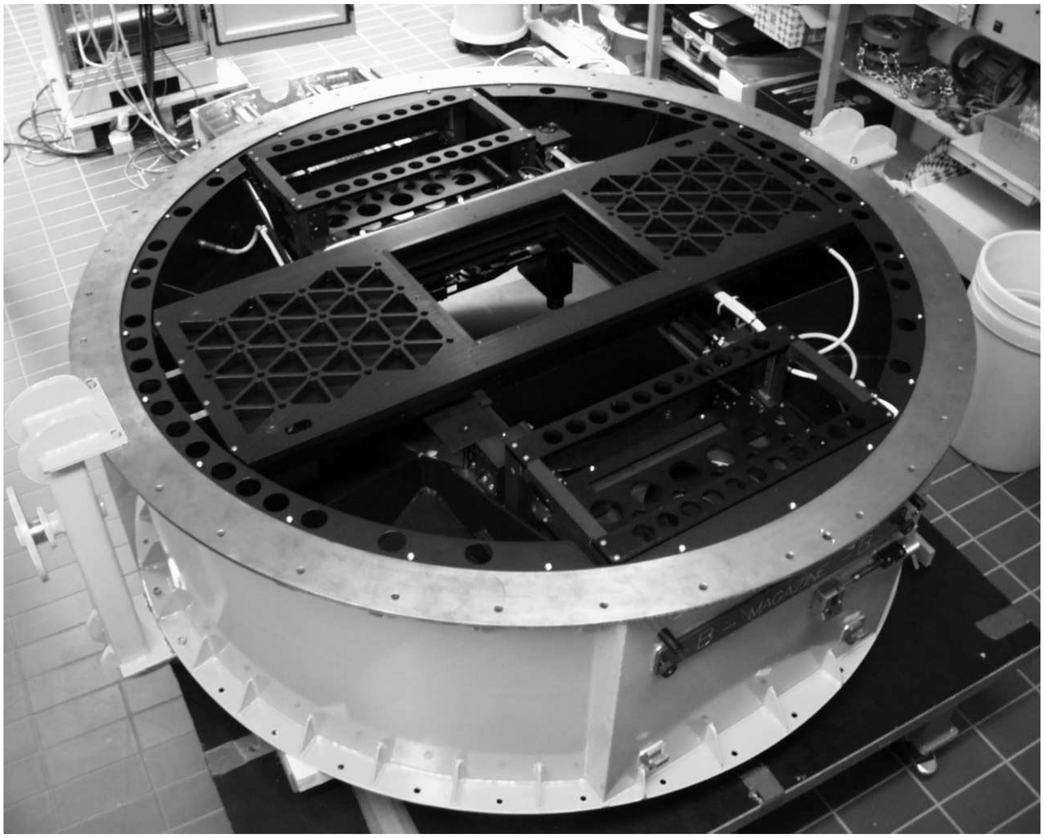

Figure 3. *The 1.5m diameter housing structure with integrated storage magazines for filters (in the upper and lower part of the photo) and shutter (structure going from left to right). Each magazine can be filled with up to 6 filters.*

motion guides. These movements are controlled such that each individual CCD pixel 'sees' the opening edge of the one blade and the closing edge of the other blade with an identical time difference, even if the blades are still accelerating—this provides an impact-free, high-accuracy photometric shutter. Tests of the shutter have shown that the performance is much better than the specifications: for an exposure time as short as 1 second, deviations from a homogeneous exposure are well below $\pm 0.2\%$ over the whole field of view. The exposure delay for individual image columns resulting from the finite blade speed can be exactly predicted.

The OmegaCAM instrument control electronics follows the well established ESO standards. To facilitate the user interface, coordination, testing and maintenance of the instrument a UNIX based workstation with high level control SW communicates via LAN to a Local Control Unit (LCU). This LCU is based on a VME system equipped with a Motorola CPU board running under the real time operating system VxWorks as well as a set of specialized control and interface boards. A dedicated calibration system provides the user with reliable data. The instrument control hardware is fully embedded into the observatory alarming system thus facilitating effective and reliable operations.

The thermal load of the instrument (a few Watt) is negligible due to locating the big drives with high loads (the magazine lifting motion and the filter exchange) outside the instrument housing. This leaves only drives without loads (like docking or locking), and able to self-lock, inside the instrument.

Figure 4. *The OmegaCAM exposure shutter. The aperture size is 370×292mm, the shortest possible exposure time is smaller than 1msec, the deviations of the effective exposure time from pixel to pixel (homogeneity) are smaller than ±0.3% for a 0.2sec exposure, the exposure time accuracy is about 0.3msec. The laptop is shown for scale.*

2.3. Optics

The VST telescope will work in two configurations, which can be selected remotely. In the standard configuration, foreseen for work at small zenith distances, a two-lens field corrector is used. The second configuration replaces this corrector with one including an Atmospheric Dispersion Corrector (ADC), consisting of one lens and two counter-rotating prism pairs. The operating wavelength ranges are 320–1014nm and 365–1014nm for the two-lens corrector and corrector + ADC respectively.

The only optical parts located in the instrument are the filters, and the entrance window to the cryostat, which doubles as a field lens.

The primary filter set of OmegaCAM will be a set of Sloan u', g', r', i' and z' filters. In addition, there will be Johnson B and V filters for stellar work and for cross-calibrating the photometric systems, a Strömgren v filter, an Hα filter consisting of 4 segments with redshifts of up to 10000km/sec, and a segmented ugri filter for efficient photometric monitoring of the sky.

Filters are being manufactured by SAGEM in Paris, and by Barr Associates in Massachusetts, and consist of 3-layer sandwiches of coloured or coated glass plates. The expected throughputs of the Sloan filters are very high (Fig. 5). The first filter (r', see Fig. 6) is being actually (May 2004) tested.

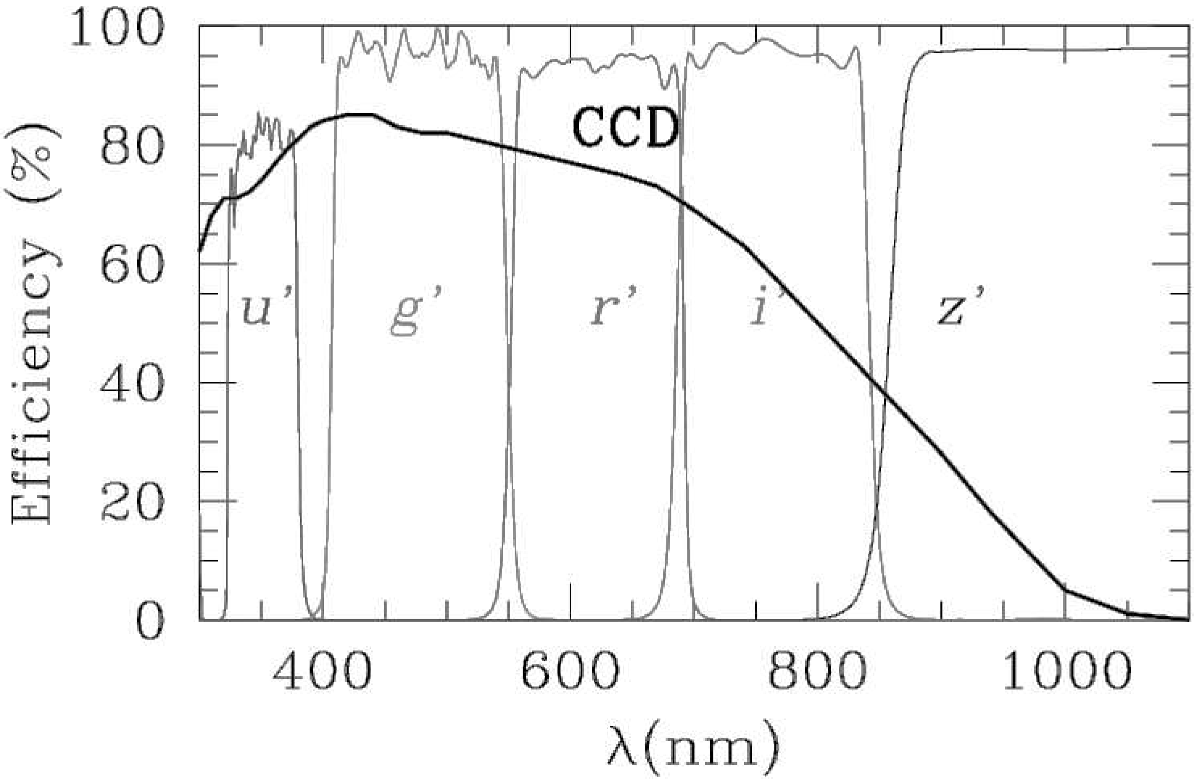

Figure 5. *Theoretical throughput curves from SAGEM for the SDSS filter set, and measured quantum efficiency of one of the OmegaCAM CCDs.*

2.4. Control Software

All instrument functions (filter exchange, shutter, detector readout, as well as monitoring the instrument state) are controlled in software[6]. The programming environment is defined and provided by ESO through the releases of the VLT Common Software which has to be used as the basis for design and development. The partitioning of the OmegaCAM Instrument Software (OmegaCAM INS) into software subsystems follows also the VLT standards. Nevertheless there were several challenges peculiar to OmegaCAM.

The *Autoguiding Software* and *Image Analysis* modules normally belong to the Telescope Control Software. In the case of OmegaCAM it was necessary to move these functionalities to the INS because during normal operations the VST guiding arm will not be used, as it slightly vignets the science array. A new software algorithm was developed to extract optical aberration coefficients from the out-of-focus images recorded on the Image Analysis CCDs[7]. On the detector software side, particular attention had to be paid to the coordination of the readouts by the different FIERA's, and to the efficient storage of the data on disk.

There are few features in the control software which increase the ratio of the shutter-open time to the whole time necessary for taking a given observation:

1. Performing setup/preset during the readout.
2. Pre-positioning of the magazine drive for the next filter.
3. Telescope offset during readout.

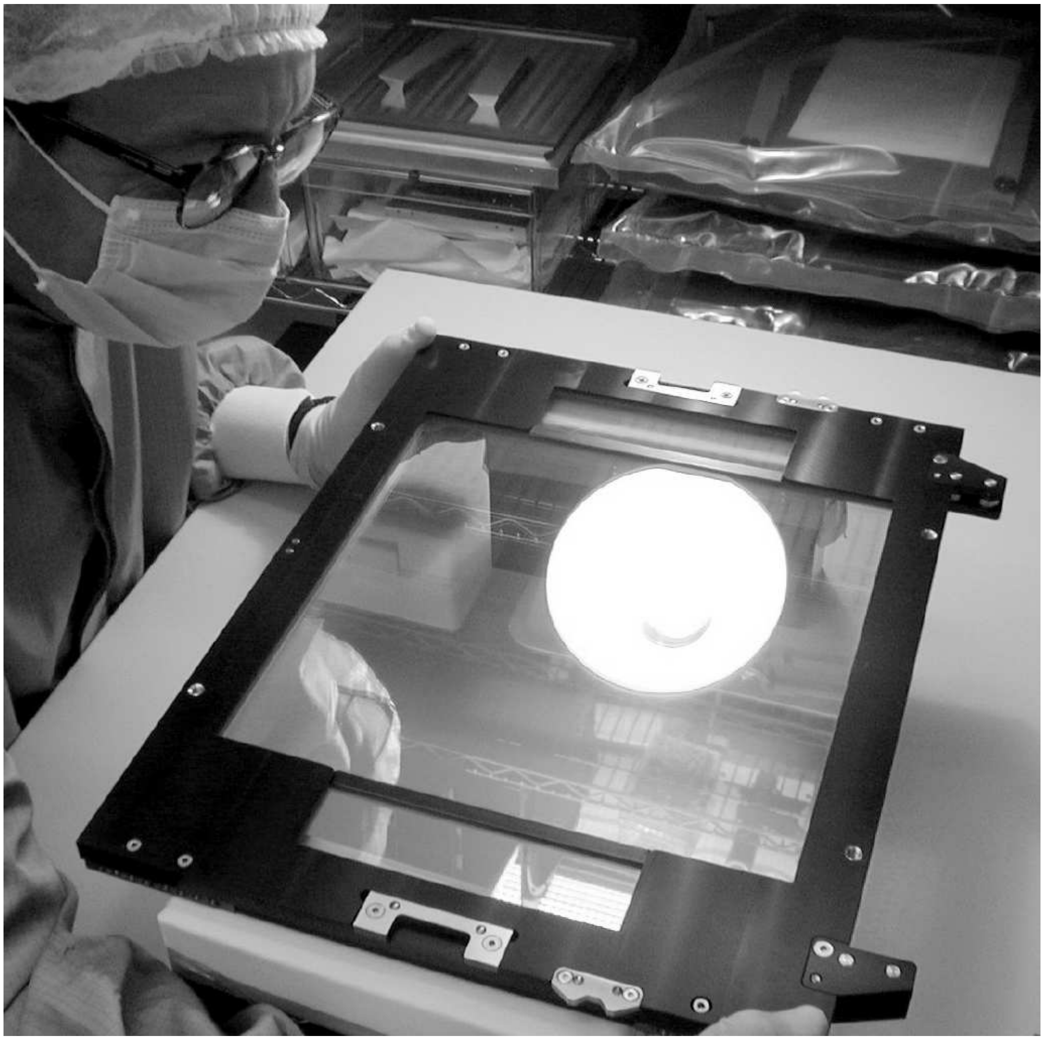

Figure 6. The r' filter in optical lab of the manufacturer SAGEM. The overall size of the frame is 424×326mm. The total mass is 6kg. In the center the 268×268 main field of view (science filter). Below and above science the auxiliary filters for guiding and image analysis are located.

3. CALIBRATION AND DATA REDUCTION SOFTWARE

The amount of data produced by OmegaCAM will be truly huge. We estimate that there will be over 15 Terabyte of raw data per year. This raw data volume contains roughly 5 Terabyte of calibration data and 10 Terabyte of raw science data. Data processing will then produce another 10 Terabyte of reduced science data and may create, with about 100000 astronomical objects per OmegaCAM field, enormous catalogues. To efficiently handle this data volume the data acquisition, calibrations and the pipeline reductions are strictly procedurized, a key aim being to maintain the *instrument*, not individual data sets, calibrated at all times. ESO will operate the instrument in service mode, optimizing the observing programme to ambient conditions, and routinely taking calibration data. Thus each night the instrument's overall responsivity and also the transmission of the atmosphere will be monitored in the u', g', r' and i' bands irrespective of the schedule of science observations. Data reduction recipes, run in ESO's DFS, will provide a continuous characterization of the behavior of the instrument in these *key* bands. When other filters are used, the calibration plan foresees a cross calibration of these filters versus these key bands.

The basic technique to overcome any gaps or artifacts in the CCD pixels is to take more exposures of the same field with slightly shifted field center and to co-add the images off-line. We distinguish the following observing modes:

- *Dither* has offsets matching the maximum gap between CCDs, ∼400 pixels (5.6mm). It will be operated with N (with 5 as the default value) pointings on the sky. Although this will nearly cover all the gaps in the focal plane and maximizes the sky coverage, the context map of such data is complex. An advantage is that it will be relatively easy to couple the photometry among the individual CCDs.
- *Jitter* has offsets matching the smallest gaps in CCDs ∼5 pixels. This mode optimizes the homogeneity of the context map and will be used during observations for which the wide gaps are not critical, but which, for instance, require a well-mapped smoothly varying PSF.
- *Stare* allows re-observing one fixed pointing position multiple times. It is the main workhorse for monitoring the instrument and allows detection of optical transients.
- *SSO* is the mode for observing Solar System Objects, which requires non-sidereal tracking.

For all these modes dedicated observing templates have been developed.

An observing strategy employs one or a combination of the basic observing modes. It also defines a number of additional instructions for scheduling of the observations. We distinguish the following strategies:

- *Standard* which consists of a single observation (observation block)
- *Deep* which does deep integrations, possibly taken at selected atmospheric conditions over several nights
- *Freq* which frequently visits (monitors) the same field on time scales ranging from minutes to months and has overriding priority on the telescope schedule
- *Mosaic* maps areas of the sky larger than 1 degree, which is essentially an item for the scheduling, as the pipeline has to produce uniform quality data anyway. The combination of various field centers into one image is not considered a standard pipeline task.

The observing modes and strategies are fully integrated with the data reduction software being developed by the OmegaCAM consortium. We distinguish between a *calibration pipeline* producing and qualifying calibration files, and an *image pipeline* that applies the calibration files to raw data and transforms them into astrometrically and photometrically calibrated images.

We have set up the EU-funded ASTRO-WISE[8] project among European wide-field imaging groups to provide a ‘wide-field imaging survey system’ that will combine pipeline processing of image data with archiving and data mining tools. Further details can be found on http://www.astro-wise.org.

4. TESTS

Extensive hardware and software tests of the instrument have been made in the past months.

- Filter exchange and positioning mechanism
  - Functionality and performance at different temperatures (4 − 22°C)
  - Functional safety – several functions prohibit each other due to hand over of the filter optics. Those moving functions are secured via an interlock system against simultaneous motion. This interlock system is hardwired without software support.
  - Positioning accuracies
  - Stability of the filter in the light path – 3pixels were specified, the goal was 1pixel. Due to lack of any play the elastic displacement was measured to about 15micron, therefore goal was reached for slewing from zenith to horizon. The residual flat field variation form this effect will be much less than 1/1000.

  - Motor current and voltages
  - Filter exchange time varies from 44 to 104 seconds depending on how far the magazines need to move and on whether the incoming and outgoing filter belong to the same magazine or not.
  - Stability of the positioning systems – magazine driving spindles, carriage driving tooth belts, docking, locking devices and notches
  - Actual loads

- Exposure shutter

  - Functionality and performance in the full functional range required for the VLT instruments (from -10 to $+30$C) – the shortest exposure time is below 1ms (specified 100ms), the deviations from homogeneous exposure over the whole field of view are smaller than $\pm0.3\%$ at 0.2sec exposure time (specified $< \pm0.2\%$ at 1 sec exposure time)
  - 'Endurance' test with 10 million up/down movements without any failure. After about 4 months of continuous operation the test was switched off. No indications of critical abrasion could be found.

- Tests of the safety measures (hardware interlock system, simulation of alarm conditions).
- Tests of the control, maintenance and observation software.
- Tests of calibration and data reduction software.

5. CURRENT STATUS

At the time of writing the acceptance tests for the 'non detector' part of the instrument are being finished. The detector system is about to be integrated into its final configuration. After testing, it will be integrated with the rest of the instrument for final system tests. Shipping to Paranal is foreseen for the February 2005.

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