OmegaCAM: the 16k×16k CCD Camera for the VLT Survey Telescope

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1. Introduction

In 2004, OmegaCAM will start operations on Paranal as the sole instrument on the 2.6-m VLT Survey Telescope. OmegaCAM is a huge optical CCD imaging camera: its 16k × 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 50 GByte 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 (encoded in the Observation Blocks) combined with highly automated processing of the data. Exciting and challenging times are ahead!

In this article, the OmegaCAM consortium presents the basic features and design of the instrument.

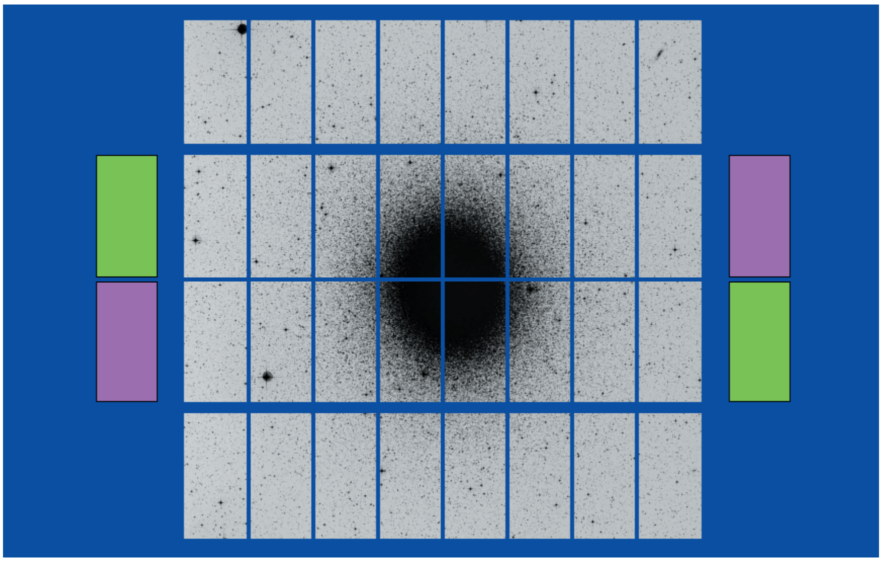

Figure 1: Layout of CCDs in the focal plane. This arrangement minimizes the amount of dead space between devices, given the constraints imposed by connecting the read-out ports. The globular cluster ω Cen is superimposed on the field, which covers a 1×1 degree area. The auxiliary CCDs, shown in green and purple, are used for autoguiding and for online wavefront analysis.

2. The VLT Survey Telescope

The VST (Arnaboldi et al. 1998), now under construction in Naples, is a 2.6-m modified Ritchey-Crétien telescope which will stand next to the four UT's on Paranal. It is 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 15 μm 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 will be the sole instrument on the telescope, and will be mounted at the Cassegrain focus.

3. Overview of the Instrument

3.1 Detector system

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 2 × 4k Marconi (now E2V) 44-82 devices, for a total area of 16384 × 16384 15 μm pixels (26 × 26 cm!). The science array fits snugly into the fully corrected field of view in the focal plane of the VST, and covers an area of 1 × 1 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 2 mm in front, one 2 mm behind the focal plane), and the resulting defocused images can be analysed on-line and used to infer aberration coefficients such as defocus, coma, or astigmatism every

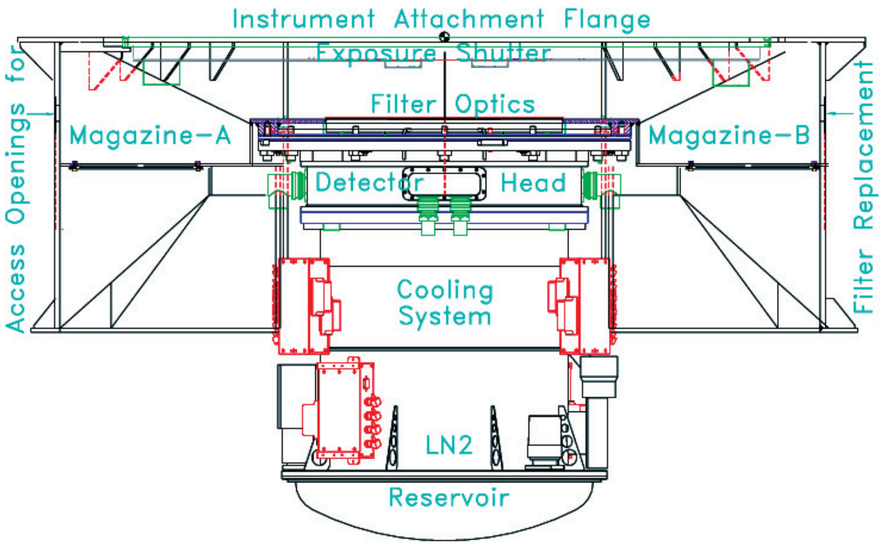

Figure 2: General drawing of the OmegaCAM instrument. The view is dominated by the cryogenic cooling system (with pre-amplifiers, vacuum equipment, etc. attached on the outside) and the detector head on top of it containing the CCD mosaic. Above the CCDs, obscuring the curved dewar window, is the filter exchange system (shown in blue), which moves filters between the two magazines and the beam. The exposure shutter is mounted at the top of the instrument, just below the telescope flange.

minute. The whole detector system is 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 45 s, and is accomplished by two FIERA controllers (a third FIERA takes care of the four guiding and image analysis CCDs).

The OmegaCAM detector team at ESO is led by O. Iwert.

3.2 Hardware

In front of the dewar window is the mechanical part of OmegaCAM: closest to the CCD window sits the filter exchange mechanism, and above that the shutter. Both components have to fit into a design space of a mere 16 cm between the dewar window and the VST's Shack-Hartmann unit. 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 housing can be seen in Figure 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. 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.

The filters are large (in the language of our latest ESO member state: a square foot) and heavy: when fully loaded with 12 filters, the instrument will contain 40 kg (90 lbs.) of filter glass alone!

The exposure shutter (Reif et al. 2002) is one of the key units of OmegaCAM (Fig. 4). It consists of two carbon fibre blades which open and close the light path. They are driven by micro-stepper motors and move smoothly on linear 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 confirm that it meets the key technical specification: for an exposure time as short as 1 second, deviations from a homogeneous exposure are well below ±0.2% over the whole field of view.

The OmegaCAM control electronics are based on VME-based local Control Units (LCUs), with a higher level of Unix-based workstations to manage the user interface, coordination, testing and maintenance. The LCU is a stand-alone VME crate equipped with a Motorola CPU board, an Ethernet board, the real time operating system VxWorks, as well as specialized control and interface boards. All the controlled functions are standardized as much as possible, and the modular design facilitates the maintenance and should ensure efficient and reliable operations.

The mechanics are designed and built by the German consortium partners in Göttingen (H. Nicklas – housing, filter exchanger) and Bonn (K. Reif – shutter). More details can be found in Nicklas et al. (2002) and Reif et al. (2002). The control electronics were designed at INAF-Naples by E. Cascone, and are being assembled at Munich University Observatory under W. Mitsch.

3.3 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

Figure 3: The 1.5-m diameter housing structure during a test assembly of the main units: the two storage magazines (to be inserted into the big shaft at left and hidden right), the filter exchange unit with the exchange carriage and a 420 × 320 mm^2 opaque, aluminium 'filter' (at the bottom left).

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 320–1014 nm and 365–1014 nm 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 10,000 km/sec, and a segmented ugri filter for efficient photometric monitoring of the sky.

The procurement of large format filters of the required size turned into a challenging task. Only one manufacturer (the French company SAGEM, formerly REOSC, who figured the VLT primary mirrors) could make an offer for producing the primary set of filters without resorting to a segmented design, which would have created vignetting shadows on the detector array. Rather than using coloured glass – barely available in the required size – the filter passband is generated by means of multiple layer coating of up to 5 surfaces in a sandwich of three plates. The expected throughputs of the Sloan filters are very high (Fig. 5).

Filter procurement is coordinated by U. Hopp and B. Muschielok.

3.4 Control Software

All instrument functions (filter exchange, shutter, detector readout, as well as monitoring the instrument state) are controlled in software. 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 also follows 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. 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.

Figure 4: The OmegaCAM exposure shutter. The aperture size is 370 × 292 mm, the shortest possible exposure time is smaller than 1 msec, the deviations of the effective exposure time from pixel to pixel (homogeneity) are smaller than ±0.2% for a 100-msec exposure, the exposure time accuracy is about 0.3 msec. (The laptop computer gives an idea of the scale.)

The Instrument Software is being produced by the Italian part of the consortium, headed by A. Baruffolo (INAF-Padua), and is described in more detail in Baruffolo et al. (2002).

4. 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 100,000 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 behaviour 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 artefacts in the CCD pixels is to take more exposures of the same field with slightly shifted field centre 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 (5.6 mm). It will be operated with

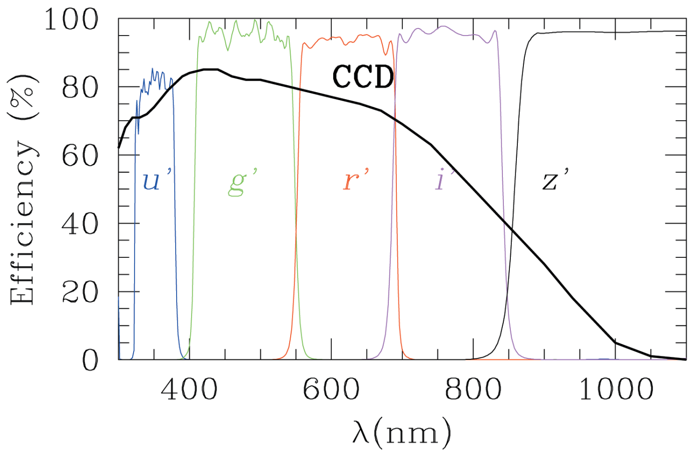

Figure 5: Theoretical throughput curves from SAGEM for the SDSS filter set, and measured quantum efficiency of one of the OmegaCAM CCDs.

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 are being 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 centres 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. ESO users will be provided with the output of the image pipeline, run in Garching, on the data contained in a single OB. The nominal photometric accuracy of this pipeline will be ± 0.05 mag, exceptionally ± 0.01 mag. The nominal accuracy for the astrometry is ± 0.1 arcsec rms over the entire field of view.

As part of the contract, the OmegaCAM consortium will deliver software modules that ESO will integrate into the image pipeline. In addition, a project has been set up 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, and in Valentijn & Kuijken (2002).

The development of the analysis software is being done by a team based in Groningen and Leiden, led by E. Valentijn.

5. Current Status

The OmegaCAM project is now well into in the manufacturing phase. Most of the CCDs have been delivered and tested; most of the mechanics exist and are ready to be integrated; instrument control and data analysis software is being coded. Extensive tests in Europe are foreseen for the second half of 2003, and the camera should see first light early in 2004. Exciting times!

Acknowledgements

The consortium was formed in 1998 in response to an announcement of opportunity from ESO, and comprises institutes in the Netherlands (NOVA, in particular the Kapteyn Institute Groningen and Leiden Observatory), Germany (in particular University Observatories of Munich, Göttingen and Bonn) and Italy (INAF, in particular Padua and Naples observatories). The ESO Optical Detector Team provides the detector system at cost to the consortium. OmegaCAM is headed by PI K. Kuijken (Groningen and Leiden University) and co-PI's R. Bender (Munich USM/MPE) and Cappellaro (INAF Naples/Padua), and project management is done by B. Muschielok and R. Häfner (USM).

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The VLTI – 20 Months after First Fringes

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1. Introduction

In 2002, the second year of fringes at Paranal, the VLTI has made substantial progress. The highlight was the completion of the combination in pairs of all four Unit Telescopes on September 15/16 and 16/17 using a total of five different baselines. Only the combination MELIPAL – YEPUN could not be provided due to the current configuration of delay lines in the interferometric tunnel.

Of equal importance was the start of a total of 150 hours shared risk science operations with the VLTI in October. Forty proposals from the community were received representing about 10% of all proposals submitted to ESO for the VLT observatory. A summary of the first semester with VLTI science operations will be given at the end of this semester. For Period 71, the shared risk science operations became a part of the ESO Call for Proposals with 25 proposals submitted for the VLTI. A number of observation preparation tools have been developed in collaboration with the Jean-Marie Mariotti Centre for Interferometry (JMMC) in Grenoble. Two of them are now available on the web (http://www.eso.org/observing/etc/ preview.html). In the course of the year, all science data between First Fringes in March 2001 and September 2002 have been released through the archive resulting in first scientific results which are described in [1]–[4]. A summary of the first results is given in [5]. In the context of science operations, the results of the on-going observations of calibrator stars are reported in [6], in collaboration with the NOVA ESO VLTI Expertise Centre (NEVEC) in Leiden.

Amongst the runners-up for achievements are the integrated optics beam