Design of the OmegaCAM Instrument Software
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ABSTRACT
OmegaCAM is a wide field optical imager that is expected to start its operations towards the end of 2003, at the VLT Survey Telescope (VST), part of the VLT Observatory, operated in Paranal (Chile) by the European Southern Observatory (ESO). OmegaCAM will almost completely fill VST one squared degree field of view with a CCD imaging mosaic 16k × 16k pixels in size. In addition to the scientific array, four auxiliary CCDs will be used for autoguiding and image analysis. Despite its conceptual simplicity and due to the large size of the CCD mosaic, OmegaCAM posed several challenges in the design of its mechanics, electronics, cryogenics and software. In this paper we report on the design of the OmegaCAM Instrument Software (INS), which is in charge of the control and operations of the instrument. We first introduce the instrument control system characteristics and the INS software development process. We then describe the main characteristics of the INS subsystems in charge of instrument functions control, autoguiding, image analysis and operations coordination. Finally, we discuss the performances expected from the software in the acquisition and storage of the large amount of data that will come from the scientific array.

Keywords: Wide-field Imager, Instrument Control Software, Autoguiding Software, Image Analysis, VST, VLT

1. INTRODUCTION
OmegaCAM is the wide field optical imager, currently being built by a Consortium of Institutes from the Netherlands, Germany and Italy, expected to start operations at the VLT Survey Telescope (VST) towards the end of 2003. OmegaCAM will feature an 8 × 4 mosaic of 2k × 4k three sides buttable CCDs for a total imaging area of 16k × 16k pixels. It will cover the VST field of view (FoV) of one square degree and at the same time it will adequately sample the best seeing foreseen at Paranal. OmegaCAM will be used to perform both surveys of large areas of the sky and dedicated observing programs. For more information on the OmegaCAM Project, please refer to the project web site at the following URL: http://www.usm.uni-muenchen.de/people/vst/WEBPA/OMEGACAM.html.

1.1 Instrument Overview
A thorough report about the OmegaCAM Instrument design and an analysis of its performance is given elsewhere. The following list details the components of the instrument that are placed under software control (see also Figure 1):

- The shutter: a two-blade photometric shutter, designed to work much like shutters normally present in reflex cameras, with a rectangular aperture of 370×292 mm. It consists of two components: the shutter mechanical unit, based on two carbon fiber blades, two linear ball bearings and driven by two stepper motors and tooth belts, and the Shutter Control Unit (SCU), a microcontroller based control electronics that runs the shutter firmware.
- The filter assembly. Due to their large size, filters mounted in the instrument are stored in two magazines, each capable of six positions. In order to load a specified filter, the magazine where it is contained is raised or lowered, as necessary, to select the requested filter; then a carriage docks to the filter and pulls it in the optical path. Unlike a “conventional” filter wheel, three motors and several digital I/O signals are required to control the filter system.
- The OmegaCAM science mosaic, composed by 32 2k × 4k three sides buttable CCDs that form a total imaging array of 16k × 16k pixels. Given the large number of devices, two ESO FIERA controllers have to be employed for their control. They must, in general, be closely coordinated by the software, with some operations performed synchronously.
- Two guide CCDs. Although the VST has its own guide system, insertion of the guide probe in the telescope FoV would vignet the science array. To provide for autoguiding signals, two auxiliary CCDs have been placed in the same optical bench as the science array, on the two opposite sides of the main mosaic, along the E-W direction.

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(vertical, in the sketch of Figure 1). Their characteristics are almost the same of the science CCDs, the main
difference being the higher vertical charge transfer rate employed for the AG CCDs.

- Two image analysis CCDs. The VST is an active telescope, but to perform Image Analysis (IA) one star has to be 
picked from the light beam using the guide probe. As for autoguiding, then, the telescope IA system cannot be used 
during observations, because it would vignet the science array. Two out-of-focus auxiliary CCDs have therefore 
been placed next to the guide CCDs and are used to collect defocused images of stars in order to perform IA.

Besides the functions in the light beam, the following sensors and controllers, which will be monitored by the 
Instrument Software, are present in the OmegaCAM Instrument:

- An inductive code reader, placed outside of the instrument on a service platform that is used during maintenance to 
insert filters in the magazines. Each filter (actually, its holding frame) is labeled with a code for its identification, 
which is read during the filter substitution procedure in order to reduce the possibility of human errors.

- Three temperature sensors used to monitor temperatures inside the instrument and two flowmeters that monitor

\[\text{OmegaCAM Instrument LAN}\]
\[\text{Instrument WS}\]
\[\text{LCU}\]
\[\text{FIERA 3 (TECH)}\]
\[\text{FIERA 2 (SCI)}\]
\[\text{FIERA 1 (SCI)}\]
\[\text{Scientific Mosaic}\]
\[\text{Filter System}\]
\[\text{Shutter}\]
\[\text{RS-232}\]
\[\text{PULPO Signals}\]
\[\text{Cryostat Cooling Ctrl}\]

Figure 1. A sketch of the OmegaCAM Control System. Due to the large size of the detector mosaic two FIERAs\(^4\) (on 
the right) are required for its control. One controller acts as the master of the mosaic: it triggers the shutter to 
open/close and slave FIERA to start integration and readout. A third FIERA (lower left) is devoted to the control of 
auxiliary CCDs. All instrument functions are controlled from the Local Control Unit (LCU) that also monitors 
temperature and flux sensors. Instrument cryogenic is controlled by the cryostat-cooling controller (middle-left), which 
is also monitored through the LCU. Software running in the Instrument Workstation (bottom) takes care of the 
coordination of operations of all subsystems and the telescope, execution of observation and provides all user 
interfaces.
the flow of the cooling fluid inside the instrument.

- An **electronics cabinet cooling controller**, that controls the temperature inside the OmegaCAM electronics rack and can generate alarms if it goes out of range.
- The **cryostat-cooling controller**, that controls the cryostat cooling system. OmegaCAM INS accesses it to read temperatures and statuses.

OmegaCAM Consortium member teams are currently building the Instrument electronics and mechanics, while the Detector System has been designed and is being built by ESO Optical Detector Team (ODT).

### 1.2 OmegaCAM Control System
The OmegaCAM Control System has been designed following the paradigm common to all VLT instruments. It is therefore a distributed system consisting of:

- one Instrument Workstation (IWS): dedicated to the coordination of operations of all subsystems and the telescope, execution of observations and provides all user interfaces;
- one Local Control Unit (LCU): a VME-based computer devoted to the control of all functions of the instrument;
- three SPARC-based Local Control Units (SLCU): they run the CCD control software. In OmegaCAM, two SLCUs control the CCD mosaic, while a third one controls the auxiliary CCDs used for autoguiding and image analysis.

The basic scheme of the OmegaCAM control system is shown in Figure 1.

### 2. OMEGACAM INSTRUMENT SOFTWARE ENGINEERING

#### 2.1 Software Development Process

The software development process that has been adopted for the OmegaCAM INS has been derived from the “traditional” waterfall approach, consistent with the general model devised for the VLT Software Management Plan. It consists of the following phases and milestones (see Figure 2):

- **concept exploration** phase: consists in the first exploration of the user needs for the OmegaCAM Instrument from a software point of view. It produces the definition of software requirements in very broad, non-technical terms;
- the output of the concept exploration phase is reviewed at the Conceptual Design Review (CDR);
- **requirements** phase: when the general design of the instrument considered as one system is started, specific requirements to the software are defined and formalized in an Instrument Software User Requirements Specification;
- **analysis** phase: comprises the general design of the software. The analysis defines the functional design of the baseline configuration of the instrument, namely: the structure of the software, the main functions of each part and the interface to others, the main design choices, the main implementation constraints (e.g. the use of ESO software).

![Figure 2. Sketch of the OmegaCAM Instrument Software Development Process.](image-url)
• the outputs of the requirements and analysis phase (User Requirements Document, URD, and Software Functional Specification, SFS) are reviewed at Preliminary Design Review (PDR);

• design phase: for each software module identified during analysis, the way of implementing its function is defined. The design provides the input to the implementation and test of the modules. It defines: the functionality provided and their implementation (classes), the software interfaces to other modules, the User Interface Mock-Ups, test plans and procedures.

• the outputs of the design phase (Software Design Documents, SDD, for all subsystems) and the revised URD and SFS are reviewed at Final Design Review (FDR);

• implementation phase: for each module the implementation consists of the development of code for all the functions, test of the code as an independent part, development of code for all test programs used in the test phase, writing the user documentations (Software User Manual and Software Maintenance Manual);

• integration and test phase: the various pieces of software are put together and with the hardware to form a working configuration of the instrument. This phase is part of the more general integration process of the instrument, which is performed at Consortium and ESO premises, in Europe. Test Reports are produced as the result of the execution of the Test Procedures defined during design using the code developed during implementation.

• after successful completion of all test procedures, the instrument (incl. the software) is said to have successfully passed Preliminary Acceptance in Europe (PAE).

• commissioning phase: the software is installed at the final site (Paranal Observatory), and the on-site acceptance is performed. On-site acceptance testing (or commissioning) consists of a repetition of integration testing, but includes also a number of tests that can be carried out on the actual site only, because of the availability of the real interfaces to the telescope and the observatory communication subsystems. Its main purpose is to demonstrate from the user’s point of view the effective coverage of the system requirements.

• after successful completion of commissioning activities, the instrument is said to have passed Preliminary Acceptance in Chile (PAC).

Other activities and milestones follow PAC, but, after this milestone has been reached, software development is essentially finished. All required functionalities are in place and have been tested, from this moment on, INS undergoes maintenance activities only.

Given its increasing popularity, and as an effective way of communication, the Unified Modeling Language, UML, has been adopted for the creation of all the analysis and the design diagrams.

2.2 Programming Environment and Standards

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. It consists of:

• supported languages: C, C++ and Tcl/Tk;
• development tools: GNU Tools (emacs, make, etc.);
• operating systems: HP-UX 11 and VxWorks 5.4;
• computer hardware: HP Workstations, Motorola PowerPC VME boards;
• source code control: CMM (ESO proprietary system).

Programming practices must follow the standards set forth by ESO that defines: programming style, naming conventions for software objects, files, etc., directory structure for software modules, standard Makefile for module compilation and installation in integration environments.
3. OMEGACAM INSTRUMENT SOFTWARE DESIGN

3.1 Software Architecture

The partitioning of the OMEGACAM INS into software subsystems follows the standard partitioning common to all VLT instruments control software.

OMEGACAM INS therefore consists of (see also Figure 3):

- Instrument Control Software (ICS): is in charge of the control of the opto-mechanics. ICS is divided in a real-time part, running in the Instrument LCU, and a monitoring and supervisory part, that runs in the IWS.
- Detector Control Software (DCS): controls all functions belonging to the detector sub-system and transfers detector data in the IWS. Here again, the real-time part of the software runs in the SLCU, while the supervisory and monitoring part of the software runs in the IWS.
- Observation Software (OS): is in charge of the coordination of all instrument subsystems and the telescope, and of the creation of data files to be delivered to the archive. It runs entirely in the IWS.

Besides the so-called standard subsystems listed above, in OMEGACAM two additional software subsystems are part of the Instrument Software:

- Autoguiding Software (AG): takes care of guide stars selection and of the computation of autoguiding and derotation corrections, that are then forwarded to the telescope control software (TCS).
- Image Analysis software (IA): is in charge of deriving the aberrations in the telescope optics from in and out of focus images of the telescope pupil, taken with two dedicated auxiliary CCDs, by means of a curvature-
like method. Aberrations are then read by the Telescope Control System that eventually computes and applies active optics corrections to the primary and secondary mirrors.

These two subsystems are usually considered part of TCS, but, for the reasons described in §1.1, in OmegaCAM they must be part of INS.

In the following sections we describe the main characteristics of OmegaCAM INS subsystems just introduced.

3.2 Instrument Control Software

In the standard ESO INS architecture, Instrument Control Software (ICS) is the software subsystem devoted to the control of the hardware.

In the OmegaCAM case, ICS takes care of interacting with the flat field lamps, the diagnostic sensors (three temperature sensors and two flowmeters), the filter system, the cabinet cooling controller, the cryostat cooling controller and the shutter (but only during maintenance operations, for normal exposures the shutter is triggered by a FIERA controller, see next section).

Since the OmegaCAM filter system is quite different from the “conventional” filter wheels (§1.1), the way in which it is operated can largely affect the duty cycle. For this reason ICS has been designed to perform each filter exchange in the most efficient way.

As already mentioned in §1.1 above, the filter system is equipped with an inductive code reader that allows to identify a filter while it is being inserted in or removed from the instrument. Since filter replacement operations are performed under software control, this mechanism allows checking that the filter that is being serviced was really the one that was asked for. By taking into account that the OmegaCAM instrument is meant to be used mainly for survey work and in service mode of observing, this extra level of checking will contribute in reducing (eliminating?) the possibility of human errors that may hamper the observing programs.

3.3 Detector Control Software

In Figure 4 we give a sketch of the configuration of the OmegaCAM Detector Control System and its connection to the Instrument Software that resides on the Instrument Workstation (IWS).

As already mentioned, due to the large number of outputs and the need to operate auxiliary CCDs in a different way with respect to the scientific ones, three FIERA controllers are employed in OmegaCAM. They are identified in Figure 4 as FIERA1-3. Each of the first two FIERAs controls half of the scientific array (i.e. 16 chips). The instrument shutter is

![Figure 4. Overview of the OmegaCAM Detector Control System](image)
controlled by FIERA1 through a standard ESO DCS temperature and shutter controller (PULPO), which is connected to the Shutter Control Unit (SCU). The third FIERA controls the auxiliary CCDs for autoguiding and image analysis. They are configured as two cameras each composed of 2 CCDs located on opposite corners of the scientific array.

In the OmegaCAM INS two instances of the DCS control the scientific mosaic, two other instances control, respectively, the autoguiding and image analysis CCDs.

To ensure proper synchronization in the execution of exposures with the scientific array, the FIERA controlling the instrument shutter must act as a master, signaling the slave controller when it has to start its operations. A typical exposure is therefore performed by sending proper setup information (exposure time, readout mode, etc) to FIERA1 and 2, including instruction to each controller about its mode of operations (master or slave). The setup is then followed by a “start exposure” command that causes the slave to wait for a signal from the master before starting its operations.

FIERA1 and 2 read each half of the scientific mosaic independently, although the readout process is started synchronously. The corresponding data is then delivered on disk in the IWS as two separate files, which are then merged together by OS, along with auxiliary information coming from the other INS subsystems, into a single file ready for archival (see §3.6, below). The total volume of data generated by each scientific exposure is approximately 512 MB.

3.4 Autoguiding Software

The Guide subsystem takes care of guide stars selection and to perform autoguiding for low frequency telescope position errors and derotation corrections. Guide stars selection can be performed automatically or manually, after telescope preset, during target acquisition. After the guide stars have been selected, and during scientific exposures, for each GCCD images are continuously acquired using one window around each star. Error signals for pointing and derotation are then computed from measured centroids, they are passed to the TCS as pointing and derotation offsets. At the operator’s choice, derotation or all guiding corrections can be disabled. Since the guide CCDs share the same shutter with the scientific array, computation of autoguiding corrections are paused in between exposures on the same target. Autoguiding is then resumed (eventually allowing for telescope offsets in dithered exposures) when the shutter is opened again.

3.5 Image Analysis Software

The OmegaCAM Image Analysis subsystem is a curvature-like system, consisting of two out-of-focus CCDs, located at the edge of the corrected field of view, that allow to continuously measure the wavefront on the CCD mosaic during scientific exposures.

The Image Analysis software subsystem takes care of selecting IA stars, performing exposure with IA CCDs, computing telescope aberrations and passing them to the Telescope Control System.

The approach to aberration coefficients estimation is based on a fit of the measured images of the telescope pupil to linear combinations of suitable basis function. These basis functions are defined by the set of non-degenerate telescope aberrations, i.e. those aberrations that generate distinguishable changes in the pairs of IA images.
When Image Analysis is requested, during a scientific observation a loop of exposures is performed with the IA CCDs. At each step in the loop a windowed image is acquired around each IA star, which has previously been selected immediately after telescope preset and after autoguiding initialization. The algorithm for aberrations computation then works as follows:

- a pre-processing step (bias subtraction, flat field division, background removal and cosmic rays filtering) is applied to the IA images;
- the corrected IA images are then normalized in flux, binned 2×2 and shifted to the basis functions center;
- a fit is performed and the aberration coefficients are derived, together with formal errors.

The computed aberrations coefficients are then passed to the Telescope Control Software, that independently determines whether to apply corrections. If this is the case then it computes M1 forces and M2 positioning commands and executes them.

3.6 Observation Software

The Observation Software (OS) is in charge of setting up the instrument and performing (and controlling) exposures with the scientific and technical detectors. It coordinates all OmegaCAM INS subsystems, including autoguiding and image analysis, to which it sends setup commands and data. It also coordinates operations with the telescope and interfaces to the data archive.

OS typically receives commands from the Broker of Observation Blocks (BOB), which is the standard VLT interface devoted to the execution of Observing Blocks (that, in turn, are essentially collection of related exposures that form the minimal scheduling unit). Although some exposure control commands (stop, abort, pause/continue) can also be sent from the OS GUI, exposures can only be started by the means of OBs.

OS takes also care of merging image data taken with the FIERAs that control the scientific array into a single FITS file that is then forwarded to the archive.

4. PERFORMANCE ANALYSIS

The average duration for a typical exposure executed with OmegaCAM is expected to be around 5 minutes. Further, a number of calibration exposures (e.g. dome flats) are expected to last just a few seconds. Given the large amount of data that is generated for each exposure, it is of fundamental importance that all data acquisition operations are performed in the most efficient way, in order to maximize the time that the instrument is actually looking at the sky.

Figure 6 illustrates which subsystems are involved in the data acquisition process and the flow of data through them. At the end of an exposure, pixel data is captured from the detector front-end electronics in the SLCU through a data capture board. Pixels are reordered, depending on the output port that they are read from, and stored into the SLCU memory by the readout process. A separate process in the SLCU transmits the pixels through the network to the IWS, where another process receives them, forwards them to the user display and writes a FITS file. In the OmegaCAM INS it has been decided that each FIERA controlling half of the scientific array writes its own file and that the resulting files are then merged by OS into a single FITS file which is then forwarded to the archive software.

In order to assess the performance of the data acquisition process and identify possible bottlenecks, we performed several simulated exposures, using test front-end electronics and a hardware/software configuration as close as possible to the one that will be in place at the VST. Our performance analysis was aimed at optimizing the data acquisition process for each individual FIERA. We performed our tests with readout speeds around 350-450 Kpix/s/port, which are more likely to be employed in the final system.

After several test runs, we found that the standard FIERA software, part of the VLT common software distribution, already performs optimally in the data reordering and transfer process. The only non-optimal step was found in the data writing process, whose performance is perfectly adequate for “normal” detectors, but that was too slow for the large amount of data generated by OmegaCAM. This problem has been however easily solved by introducing a proper data buffering strategy in the data writing process.

After modification, the total time required for the completion of the readout and acquisition process is well below 40 seconds. Allowing for the overhead of coordination of the FIERA controllers and the time required for wiping the CCDs prior to each exposure, we conclude that in the final system the minimum time between consecutive exposures will be
around 40 seconds, a perfectly acceptable performance figure if we compare it with the readout time of the whole mosaic (~20-25 s, depending on the readout speed).

5. SOFTWARE PROCESS STATUS

The OmegaCAM instrument software has successfully passed Final Design Review in September last year. Since then the development phase has started and is expected to proceed up to the end of 2002, when the first version of the software will be released, ready for integration with the instrument. This phase is expected to last about six months (allowing also for all instrument and software modifications that will eventually be required) and end with Preliminary Acceptance in Europe (PAE) in mid-2003.

6. CONCLUSIONS

Despite the conceptual simplicity of the OmegaCAM instrument, the large size of its detector mosaic, and the resulting need to integrate in the instrument autoguiding and image analysis functions, has introduced additional complexity in the design of the Instrument Software. However, on the basis of the tests that we have performed until now, we are confident that in the end we will be able to deliver the expected functionality and performance, without violating the constraints of providing a software system whose design and implementation fully comply with the ESO software standards for VLT instruments.

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