NGC — ESO's New General Detector Controller

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As the replacement for ESO's standard infrared and optical detector controllers, IRACE and FIERA respectively, ESO has developed a new controller — the New General detector Controller — that will be the default detector controller for all new La Silla Paranal instruments in the next decade. The basics of its design and functionality are described, and first performance examples are given.

The invisibility challenge

In an era when professional astronomers have long abandoned the naked eye and photographic plates as scientific detectors, many users of La Silla Paranal (LSP) instruments may no longer know what happens exactly between the arrival of the photons at the detector and the first inspection of the new observation – and there should be no need to, as this process should be fully transparent to them. On the other hand, this transparency can be achieved only if the corresponding process is very robust and does not imprint signatures of its own on the data. Since this final step of any modern observation is quite complex, and should be completed quickly, there are many potential failure points, and so this largely invisible step requires much care and effort. The detector may have to be cleaned of the residue of a previous exposure, voltages need to be applied to keep the electrons generated where the photons hit the detector, a shutter may have to be opened, the exposure time must be accurately kept, a shutter may have to be closed, and a sequencer has to generate time-dependent voltage patterns to drive the accumulated electrons to the amplifier, or to address each pixel amplifier sequentially. After amplification, the charges are converted to voltages and digitised, and the resulting number must be inserted at the right location in the data block, and important ancillary information must be written to the FITS header, without which the data block would not form an image that can be processed further and scientifically interpreted.

The requirements on the precision, repeatability and invisibility of this process are quite tough: the shutter timings must be accurate to 1 millisecond; voltages specific to each detector must be repeatable at the 10-mV level; the proper shaping of readout signals requires 10-nanosecond resolution, and is different for all detector models; the analogue electronics should, at most, minimally degrade the photon noise, even of the faintest signals; and analogue-to-digital converters must oversample this system noise. This latter task is more easily appreciated if it is realised that most present-day detectors generate voltages as tiny as a few microvolts per photoelectron. In order to speed up data transfer, parallel output channels are used, but none should generate an echo of its own signal in any of the other channels. At any one moment, software and hardware-embedded firmware must keep tight control over all steps and give status reports to the higher-level control software. If something does go wrong, due to the failure of some general utility such as electrical power or computer networks, the user wants to be given a meaningful error message, which is a much less trivial task than it first appears.

The present past: FIERA and IRACE

Almost all current infrared LSP instruments employ IRACE (InfraRed Array Control Electronics; Meyer et al., 1998) to execute the above (and more) tasks, while all optical instruments use FIERA (Fast Imager Electronic Readout Assembly; Beletic et al., 1998). They are the VLT standard detector controllers. Following IRAQ (cf. Finger et al., 1987) and ACE (Reiss, 1994), they were the first standard detector controllers developed at ESO. A recent analysis has shown their downtime-weighted reliability in the first decade of operation of the VLT to have reached a level of 99.85%. The contribution of the detector systems to the total observatory downtime is thus only about one-tenth.

Why not, then, use IRACE and FIERA forever? The answer is twofold and simple: the electronics of both FIERA and IRACE include an increasing number of electronic components that are no longer manufactured and cannot be replaced by other parts. In addition, some detectors, and especially those for advanced applications such as adaptive optics and interferometry, have requirements exceeding the specifications and capabilities of FIERA and IRACE. Therefore, successors are needed. Interestingly, the first ESO instrument to bridge the conventional gap at 1 micron between optical and infrared instruments, X-shooter, took delivery of the last IRACE as well as the last FIERA systems.

The present future: NGC

After some initial debate, and successful tests of a CCD with IRACE, it became clear that it would probably not take two separate systems to replace FIERA and IRACE and that the development of a unified, wavelength-independent controller should be attempted, known as the New General detector Controller (NGC). A dedicated NGC team was formed from staff at ESO's two detector departments, namely the Infrared Detector Department and the Optical Detector Team. The strengths and weaknesses of FIERA and IRACE were analysed, requirements for future detectors and applications were solicited, taking note also of the practical needs of the LSP Observatory, and four generations of prototypes were produced and carefully tested. First deliveries have been made to the MUSE prototype, to KMOS, SPHERE and soon also to ZIMPOL, so that it is timely to present this new "invisible box" to the LSP community.

NGC architecture

Apart from the critical performance parameters, other strong design goals of the front-end electronics included modularity, scalability and compactness. While both FIERA and IRACE boxes still host a

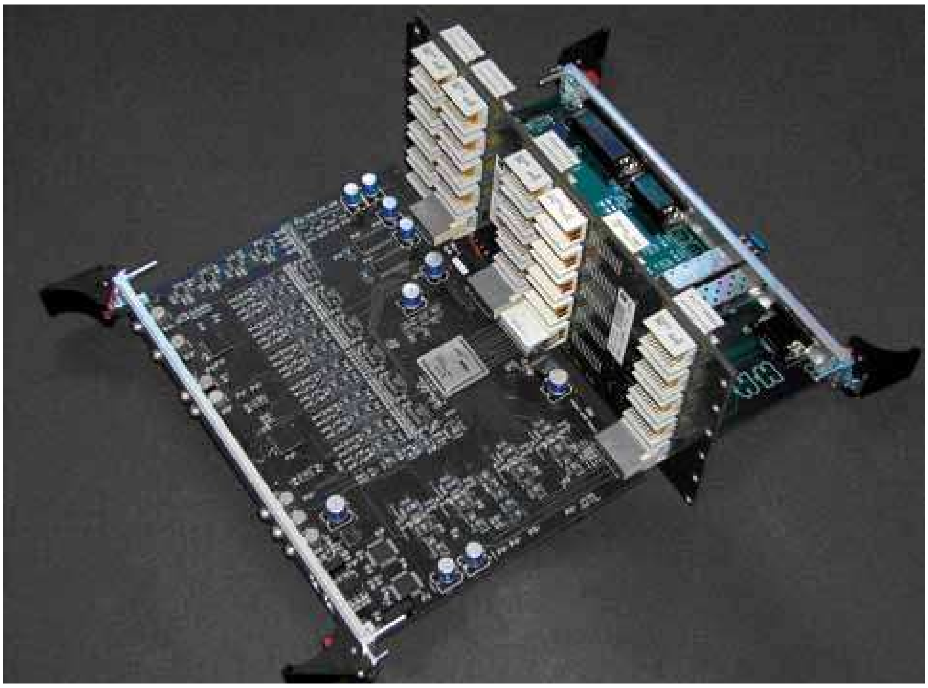
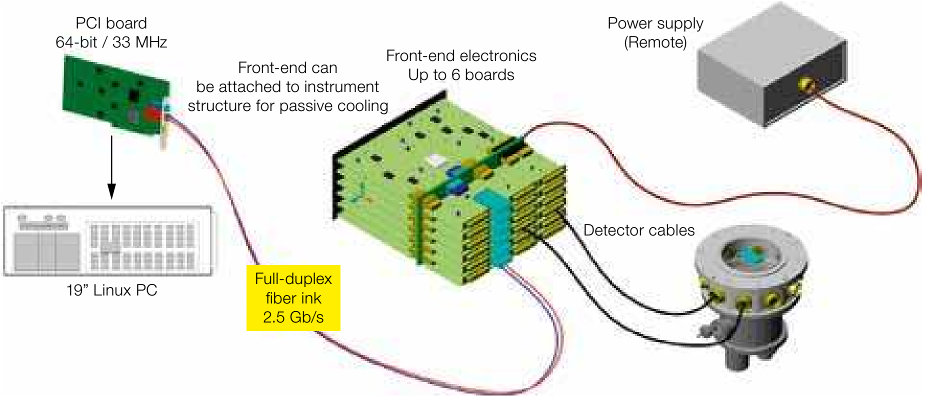


Figure 1. Minimal-configuration NGC system consisting of Basic Board (left), associated Transition Board (right), and backplane (middle).

handful of different electronic boards, this diversity is much reduced in NGC. The simplest NGC system (Figure 1) consists of one so-called Basic Board, which can handle up to four video input channels and provides 18 clocks and 20 biases. For multi-channel detectors, a 32-channel Acquisition Board is available. There must always be at least one Basic Board, but otherwise both types of boards can be combined in arbitrary quantities to form an NGC system. The heart of each board is a Xilinx Virtex Pro II Field-Programmable Gate Array (FPGA) running firmware programmed in VHDL (VHSIC Hardware Description Language, where VHSIC is the acronym for Very High Speed Integrated Circuit). Multiple boards are daisy-chained through direct FPGA-to-FPGA high-speed serial links, i.e., there is no parallel bus. Commands are passed on through the chain until they reach the FPGA to which they are addressed. Most connections with other parts of an NGC system are through two types of Transition Boards, which complement each Basic and 32-channel Acquisition Board, respectively.

Figure 2. Top-level diagram of a scientific NGC system (schematic).



Initially, FIERA and IRACE systems featured UltraSPARC-based Logical Control Units (LCUs), called SLCUs, running the low-level software required to prepare the electronics and the detector for an observation, to acquire the readout data and pre-process them in more advanced readout schemes, assemble them into FITS data blocks, possibly post-process the latter, and transfer the resulting images to the instrument workstation for subsequent inspection, online reduction, and archiving. Following successful tests, notably with IRACE, the role of the SLCUs is, in NGC systems, now taken over by PCs from the Dell PowerEdge family. They are known as LLCUs because they employ the Linux operating system. A dedicated 64-bit 33-MHz PCI interface card handles the data ingestion. Up to two PCI (Peripheral Computer Interconnect) boards can be used per LLCU, which can therefore support up to two NGC front-ends, whereas applications with very high data rates may require more than one back-end per front-end. The fibre link between front-end electronics and back-end LLCU may be up to 2 km long. A top-level system diagram of the NGC is shown in Figure 2.

For the NGC control software, there was a strong request from VLT control software engineers that the interfaces be as close as possible to the ones for FIERA and IRACE. Since interfaces for FIERA and IRACE are very different, obviously only half of this request could be fulfilled if the interface for NGC were to be homogeneous. Because the NGC hardware concept has inherited more from IRACE than from FIERA, the IRACE interface was a natural starting point. In fact, VLT infrared (IR) instrument software developers will not see much of a difference between IRACE and NGC.

Functionally, the NGC control software is divided into three parts. One of them is also the lowest layer, which handles all interactions with the NGC electronics and is used by all NGC applications. But the next layer has to pay tribute to the fact that an observation in the optical typically consists of one integration with one readout while in the infrared most observations comprise many exposures, each of which may be read out multiple times. The optical case seemingly boils down to the most trivial infrared case, although invariably requiring the use of a shutter. However, the details of the atomic readout process proper are very different. Not only can IR detectors be read out non-destructively, but they permit the build-up of the signal with the number of readouts to be fitted separately for each pixel, thereby drastically improving the data homogeneity. In CCDs, individual pixels cannot be addressed, and full images are shifted line-by-line to the horizontal or readout register, where the charge shifting continues in the orthogonal direction and pixel-by-pixel. Moreover, the different states of a CCD exposure require different voltages to be applied. Last but not least, the much higher background signal in IR data requires very different, coupled operating strategies for detector, instrument and telescope. Therefore, it is more effective to develop two separate software branches. The infrared one is again very similar to the IRACE software. By contrast, the optical part, while trying to benefit maximally from the experience with FIERA, is an all-new development. Therefore, there was freedom to test software concepts that had not previously played a major role in the VLT environment. The approach chosen is the one of a state machine, to which the various states of an optical detector controller (wiping, integrating, reading, etc.) map very well. In addition, the code for a state machine can be very effectively restructured if necessary. This is an asset not to be underestimated. The NGC project was fortunate that a state-machine approach had just been introduced to the VLT control software (the so-called Workstation Software Framework — Andolfato & Karban, 2008).

The NGC control software is an integral part of the VLT control software and, as such, participates in the annual release scheme following thorough test cycles, for which a comprehensive suite of dedicated automatic tools was developed.

Ancillary functions and peripheral devices

The three fundamental on-detector steps that eventually lead to the formation of an image are charge generation (by the incident photons), charge confinement and transport (in CCDs), and the measurement of the voltage corresponding to the accumulated charge. They are accomplished by the application of a set of time-dependent voltages, in part with a resolution of 10 ns. These so-called readout patterns are encapsulated in NGC-specific parameter files. While for exact fine-tuning a normal text editor is mostly a good choice, rapid prototyping and checking for possible conflicts is done much more effectively with a graphical editor. The tool for the latter is the Java-based BlueWave package. Since BlueWave is not directly embedded into the VLT operation it is not part of the NGC control software, but is distributed with it.

The original signals provided by the detectors themselves are so feeble that they must be pre-amplified as early as possible so that they do not get mixed with parasitic signals (pick-up noise) emitted by other devices or the electrical mains. In infrared systems, cryo-proof Complementary Metal-Oxide Semiconductor (CMOS)-based pre-amplifers are integrated along with the detectors into the cryostat heads while for the optical pre-amplifiers are located within 2 m of the respective heads. Synchronisation with external activities such as M2 chopping is supported.

Since detectors are delicate devices and, in science-grade quality, very expensive, the Transition Boards of the Basic Boards carry a sensitive, rapid-response protection circuitry to prevent overvoltage causing any damage. Likewise, failures of the input power or overheating within the NGC housing lead to automatic preventative shutdowns, which can be reported to the LSP Central Alarm System (CAS).

The NGC front-end electronics is accommodated in a custom-built housing (Figure 3). Each board and its associated transition board are plugged back-to-back into

Figure 3. Rear side of an NGC housing with connectors for power cable and cooling-liquid hoses. The width is about 440 mm; depending on application, all surfaces can be anodised. Also visible are the backplane and, on both sides, rails to guide and hold the boards, of which there may be up to six.

the backplane (cf. Figure 1), which forms the core of the housing. A liquid-based heat exchanger provides active cooling. Although the heat dissipation per Basic Board (32-channel Acquisition Board) is only about 15 W (20 W), this is necessary in order to meet the tight VLT environmental specifications on the surface temperatures of equipment installed at the Unit Telescopes (UTs). Taking into account the baseline dimensions implied by these specifications, the number of slots was fixed to six, i.e., one Basic Board and up to five more boards with their associated Transition Boards can be stacked. For many laboratory applications, a simple passively cooled two-slot housing is used.

Each NGC front-end electronics unit needs its own power supply. The initial default is a separate one-size-fits-all housing. Because of the low, and still decreasing, intrinsic noise levels of modern scientific detectors, it is filled with a number of commercial linear power supplies, although their lower efficiency results in roughly doubling the mass (and volume). These unit power supplies must be different for optical and IR detectors. Further application-specific diversification is under discussion.

FIERA-controlled optical detector systems include a general-purpose housekeeping unit, PULPO, for shutter and temperature control and pressure monitoring. However, quite a few of its components are no longer available. In NGC, the shutter control is implemented on the Basic Board. The MUSE project has developed "TeePee", which is based on the commercial Jumo Imago 500 multichannel process controller; as the name indicates it is used to handle TEmperaturE and PrEssurE. Other optical detector systems may use suitable adaptations but TeePee is not part of the NGC project. The much higher demands on temperature control of IR detectors (or ultra-stable instruments such as needed for exoplanet searches) can be met with commercial LakeShore controllers, which reach an accuracy of a few milliKelvin.

NGC-AO: NGC for adaptive optics

The NGC described so far is also called Scientific NGC as it is used to control detectors for the recording of scientific data. Another important application of digital detectors at modern observatories is signal sensing, most notably for autoguiding, active optics and adaptive optics. Since the first two applications rarely require frame rates above 1 Hz and the interface to the Telescope Control System is not too demanding, commercial detector controllers are more economical than any customised development. This is not (yet) so for adaptive optics (and interferometry) applications, where frame rates of order 1000 Hz quickly become supra-commercial when combined with the requirement of negligible read and system noise.

An agreement was concluded between ESO and e2v technologies for the custom development of an L3 Vision split frame-transfer CCD with 240 × 240 pixels and eight channels. This CCD20 (Downing et al., 2006) will be the standard detector for the forthcoming VLT adaptive optics (AO) wavefront sensors such as GALACSI (MUSE), GRAAL (HAWK-I) or SAXO (SPHERE) and generate data rates of well above 100 Mbyte/s. In a parallel effort, the observatories in Marseille, Grenoble, and Haute Provence are developing a test controller (OCam; Gach et al., 2006). The analogue part of the OCam electronics is being integrated with a specially customised part of the digital electronics of NGC to form NGC-AO. A considerable extra challenge associated with the high data rates is that the sequencer must run at subnanosecond resolution and that the controller must be within centimetres of the detector, where the constraints on volume, mass and heat dissipation are very tight. After readout, the data is directly and continuously transmitted via serial Front Panel Data Port (FPDP) to ESO's AO real-time computer system SPARTA (Fedrigo et al., 2006).

Performance and other qualities

NGC prototypes were extensively tested at all phases and with various optical and IR detectors. Not surprisingly, each hard- and software release has required some bug fixes. But in no case was a significant redesign necessary. It was very gratifying that the combination of two sets of expertise did not partly annihilate one another and cause previously unknown problems, as has been the experience with many industry-scale cooperations or mergers. A particularly welcome early observation was that images read out with NGC do not show those suspicious wavy patterns, which mostly add little to the effective overall noise, but are visually quite irritating.

Very comprehensive tests were run with the first science-grade detector for KMOS, a Hawaii-2RG device from Teledyne Imaging Sensors. The noise histogram in Figure 4 demonstrates a read noise of 6.9 e- root mean square (rms), which was achieved with simple double-correlated sampling and is the lowest noise ever reported for such a detector (cf. Finger et al., 2009). Detailed tests were also performed with the prototype detector system for MUSE, which employs a 4k x 4k CCD 231-84 device from e2v. At 50 kpix/s, a read noise as low as 2.8 e- was achieved. Using all four ports, the entire array can be read within 45 seconds and at a read noise of 3 e-. An excellent (non-)linearity of 0.3% was measured.

While system noise is the most decisive figure of merit for any detector controller, there are many more advantages to the NGC system:

– Signals can be sampled once or several times, in the analogue as well as digital domain.

– Much higher bias voltages are supported than for FIERA. This is important as it permits fully depleted CCDs, that are made of very thick silicon, to be operated, leading to the achievement of a much improved near-IR sensitivity. (Silicon becomes increasingly more transparent with wavelengths into the near-IR.)

– Gain and bandwidth of the optical preamplifier are both programmable in 16 steps, permitting sensitive matching of NGC to various types of CCDs and readout modes.

– An NGC system can go online within just 3 seconds (longer if more configuration checks are performed), and detector engineers appreciate that, in the laboratory, they can make a warm start after having changed voltages so that test sequences can be executed with high time efficiency.

– While a FIERA front-end with four video channels comprises 5373 electronic components, of which 286 are different, these numbers are 1697 and 91, respectively, for NGC so that parts procurement and stock-keeping are much simplified.

Outlook

NGC will be the standard detector controller for future LSP instruments, regardless of wavelength. For the existing instruments, FIERA and IRACE fulfil all requirements, and there are enough spare parts to sustain the unrestricted functioning of all systems throughout the lifetimes of their host instruments. Like FIERA and IRACE, NGC will be a line-replaceable unit at the observatory. Because of the increasingly specialised demands from both new detectors and new applications, NGC will develop into a toolkit, which permits ambitious projects to be realised on one common platform, but with a minimum number of actually-used variants. For instance, new 3-MHz analogue-to-digital converters (ADCs) are being tested for their suitability to replace the current default 1-MHz ADCs for higher-speed applications. A special high speed (10 MHz) development is also underway. Software for standardised low-level post-processing of data (e.g., averaging of frames or bias correction) on the LLCU is under development. NGC will continue to serve as the basis for close collaborations between the Infrared Detector Department and the Optical Detector Team, and a joint NGC production line has been set up. Extrapolation from the experience with FIERA and IRACE suggests that, in all probability, a full-blown second generation NGC will be needed to support the E-ELT operations due to start in 2018. By then many detectors may come with their own on- or near-chip controllers (ASICs — application-specific integrated circuits). But they will need a common E-ELT umbrella to interface to the overall E-ELT control system and operations paradigm.

Additional technical information including numerous downloadable documents is available on the NGC home page[1]. The section "General" contains pdf versions of a number of detailed presentations about various aspects of NGC (design, production, testing, performance). The NGC Team welcomes your enquiries and feedback at ngc@eso.org.

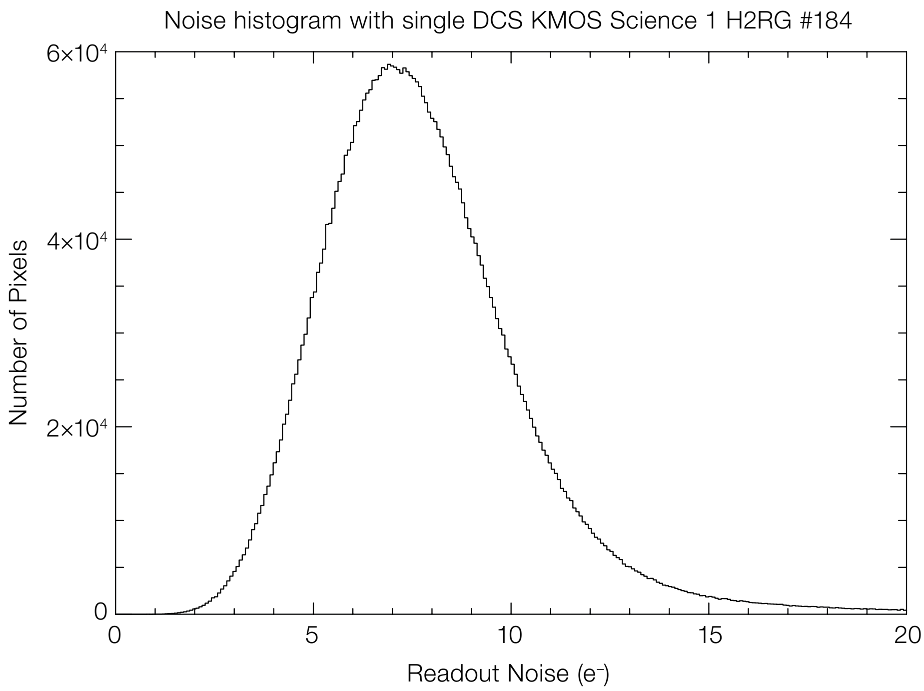


Figure 4. Noise histogram for single double-correlated readout of a 2K x 2K HgCdTe substrate-removed λ_c = 2.5 μm Hawaii-2RG array (KMOS science-grade array #1). The noise distribution peaks at 6.9 electrons (rms).

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Links

[1] http://www.eso.org/projects/ngc/