OPTICAL DETECTOR SYSTEMS AT ESO

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Abstract: An introductory overview is given of the optical detector projects that were started or completed at ESO since the DfA2005 workshop (Beletic et al. 2006). They fall into four main categories: detector controller, scientific detector systems, research and development, and signal (wavefront) sensing. Most of them are presented in more detail in other contributions to DfA2009.

Key words: CCDs, detector controllers, wavefront sensing, CMOS

1. INTRODUCTION

This paper continues two previous, similar status reports (Baade et al. 2004, Baade et al. 2006). As before, detector controller development, new scientific detector systems and upgrades of existing ones, research and development projects, and wavefront sensors for adaptive optics account for the bulk of the work done. They are presented in turn below. ESO's progress in the infrared detector domain is outlined by Finger et al. (2009).

One further standing responsibility of ESO's Optical Detector Team in Garching, namely the support of corrective maintenance of optical detector systems deployed at ESO's La Silla Paranal Observatory, once more required almost no time because the reliability continued to be excellent. In the framework of the reliability analysis of the New General detector Controller (NGC, see next section), the downtime of detector systems based on the NGC predecessors FIERA and IRACE was analyzed (Baade 2008). It showed that the average availability in the first decade of VLT operations through 2008 May reached 99.85%. The mean time between failures was 54 days.

2. NEW GENERAL DETECTOR CONTROLLER (NGC)

With the beginning of the operations phase of the Very Large Telescope (VLT), ESO introduced two new standard detector controllers for (nearly) all of its optical and infrared instruments. A decade later, the X-shooter project (see below) took delivery of the last FIERA and IRACE controllers. Because of the obsolescence of critical parts and the much evolved requirements of new detectors, further copies will not be produced anymore. The next VLT instrument projects - MUSE (24 CCD231 devices from e2v, see below), KMOS (three Hawaii2 RG detectors from Teledyne), SPHERE (one Hawaii1 and two Hawaii2 RG devices from Teledyne), and ZIMPOL (two e2v CCD44-82 detectors in frame-transfer mode, see below) - are already being supplied with the common successor of FIERA and IRACE, NGC (New General detector Controller).

Such so-called scientific NGC systems consist minimally of one Front-end Basic Board (FEB) and one associated Transition Board (FEBT). This configuration offers control of 18 clocks and 20 biases. In principle, an arbitrary number of pairs of FEBs and FEBTs can be combined. For multi-channel detectors, additional 32-channel acquisition boards (32AQ) are available, which require their own type of transition board. The standard water-cooled 6-slot housing can accommodate any combination of FEBs and 32AQs, provided there is at least one FEB. A rich menu of modes is offered, e.g., sample up-the-ramp, Fowler sampling, digital double-correlated sampling, analog clamp & sample, etc. The price to be paid for this versatility and the support of both IR and optical detectors is a relatively large number (> 40) of jumpers needed to configure an FEB for its specific application. But any reconfiguration can be done in 5 minutes or less.

The data rates possible with these boards is limited by the 1 MHz A/D converters. But adaptive-optics (AO) and interferometry applications require higher throughput. Therefore, additional high-speed variants to be used with, e.g., Raytheon Aquarius detectors (3 MHz) and Selex eAPDs (10 MHz) are currently being tested. At optical wavelengths, the coherence time of the atmosphere is significantly shorter still, and a completely new branch of NGC is underway (Reyes and Conzelmann 2009). It incorporates the OCam analog electronics (Feautrier et al. 2009) and reaches 14 MHz in each of 8 channels. As described below, this camera and CCD220 from e2v will be the standard for the new generation of AO systems at the VLT.

NGC is a joint project of the two detector departments at ESO, IDD and ODT. Further details of the capabilities and design principles of NGC are elaborated in Meyer et al. (2009), Cumani and Stegmeier (2009), and Baade et al. (2009).

3. DETECTOR SYSTEMS FOR SCIENTIFIC INSTRUMENTS

3.1 X-shooter

X-shooter is the first ESO instrument that bridges the traditional gap near 1 μ between optical and infrared instruments. This medium-resolution echelle spectrograph divides its wavelength coverage in three segments: (UVB 0.3-0.56 μ; MIT/LL CCID-20), VIS (0.55-1.02 μ; e2v CCD44-82), and IR (1.02-2.48 μ; H2RG). There is some irony in the fact that this UV and IR unifying instrument came too early for NGC and so became the last one still delivered with FIERA and IRACE. In order to save mass and volume, the FIERA software was enhanced such that one DFE can support two virtual cameras corresponding to the two optical wavelength ranges. In 2008, X-shooter was successfully commissioned at the VLT.

3.2 MUSE

With a field of view (FoV) of 1 arcmin x 1 arcmin, the ambitions of MUSE are more in the domain of angular resolution (0.3-0.4 arcsec with adaptive optics) and spatial depth (up to a redshift of 6 for quasars with strong Lyα emission). This concept results in the need for a considerable number of pixels with excellent point-spread function (PSF). The FoV is sliced up into 24 subareas, each of which is covered by its own unit spectrograph. Twenty-four identical detector systems are centered around e2v CCD231 4k x 4k DD detectors. The number of 0.4 Gpixels corresponds to a 16k x 24k mosaic, making the MUSE detector system one of the largest in the world (especially among spectrographs) and even surpassing the dimensions of OmegaCAM by 50%. Almost 50,000 spatially independent spectra can be taken with one exposure.

During phases of excellent seeing, MUSE will just critically sample the atmospheric PSF, placing strong requirements on the contribution from the detectors. With a virtual knife-edge test (scanning a small spot across the pixel) the latter was determined to decrease from ~1 pixel at 465 nm to ~0.6 pixel at 930 nm. For deep-depletion devices, i.e. with a thickness of 40 μ, these values are considered fairly good. Four 6-slot NGC units will control the 24 detectors such that they act as one single detector system. At

100 kpix/s (40 s readout time), the read noise will be better than 3 e^-. A special challenge to be overcome is the safe control of the coolant distribution to 24 unit cryostat. More specific information is available in Reiss et al. (2009).

3.3 ZIMPOL (SPHERE)

A variant of the Zurich Imaging Polarimeter (ZIMPOL) forms part of the exo-planet finder SPHERE. Its purpose is to exploit the polarization signature of scattered light to make coronography-assisted direct images of planets orbiting nearby stars. Two CCD44-82 detectors record two orthogonal polarization stages simultaneously and also rapidly alternate between them. In order to overcome variability in the Earth's atmosphere, this polarization modulation takes place at 1 kHz. At exactly the same rate the charges are shifted back and forth on the CCDs. The latter are covered with a mask of opaque stripes so that light in both polarization states is recorded by the same pixels (but at slightly different times). This very high level of differentiality of the measurements strongly suppresses any systematic errors. Because star-to-planet contrast ratios of up to 10^8 need to be overcome, only about 20 solar-like stars will be within reach of SPHERE/ZIMPOL even when mounted to the 8-m VLT. With such stars, the detectors are exposed to a significant fraction of full well within 1 s, which is the typical integration time. Frame-transfer CCDs and two cameras are used to reach a duty cycle of nearly 100% for both polarization states. A first engineering version of the detector system was delivered in Q4/2009. The science-grade version is foreseen for Q1/2010.

3.4 OmegaCAM

The 16k x 16k detector system of the wide-field imager of the forthcoming 2.6-m VLT Survey Telescope (VST) on Paranal, OmegaCAM, was presented at DfA2005 by Iwert et al. (2006), and it was not expected that it would feature at another *Detectors for Astronomy* workshop since it is ready for commissioning. However, during the otherwise very successful re-assembly of the instrument on Paranal it was discovered that one of the 32 CCD44-82 devices in the mosaic displayed signs of severe malfunctioning. According to the remote diagnosis kindly provided by e2v, the reason might be an inner short. A similar problem had already been encountered with one of the OmegaCAM spare CCDs while it was being tested on ESO's CCD test bench. Following detailed planning and careful preparation, the faulty detector will be replaced in November/December, 2009. But, since it is not understood why such problems occur in spite of very cautious treatment and years after the delivery, there is concern that future thermal cycles may trigger failures also of other CCDs in the mosaic.

3.5 Detector upgrades of optical VLT instruments

FORS1, GIRAFFE, and UVES, received new detectors between 2007 and 2009; VIMOS will follow in 2010. In all cases, the main objective was to increase the overall sensitivity. While FORS1 is the blue-sensitive part of FORS so that the emphesis was on the blue wavelength range, the other three projects aimed at bringing the red quantum efficiency closer to the blue/green one. This was possible thanks to the increased silicon thickness enabled by higher depletion, which is now also commercially offered. In the area of CCDs, this is clearly the most important advancement achieved in the past couple of years. The most extreme variant appearing on the commercial horizon employs bulk silicon and is the current record holder in near-IR quantum efficiency of CCDs (Downing et al. 2009a). Many users probably value the much reduced nuisance of fringing at least as much, which results from the higher thickness (and, in the case of fixed-format spectrographs, can be suppressed further by graded antireflection coating). The accompanying modest increase in dark current is negligible for most applications, and the higher sensitivity to particle radiation can usually be overcome with split exposures. Table 1 summarizes the detector replacements made and the results achieved.

	FORS1	**Giraffe**	**UVES (long-wavelength CCD of red arm)**	**VIMOS**
Instrument type	Focal reducer	Medium-resolution multi-object spectrograph	Echelle spectrograph	Wide-angle multi-object spectrograph
Year of re-commissioning	2007	2009	2009	2010
Old detector type	Tek 2048EB4-1 2kx2k, 24-µ pixels	e2v CCD 44-82 2kx4k, 15-µ pixels, 20 µ standard silicon	MIT/LL 2kx4k, 15-µ pixels, 20 µ standard silicon	4x e2v CCD 44-82 2kx4k, 15-µ pixels, 20 µ standard silicon
New detector type	2x e2v CCD 44-82 2kx4k, 15-µ pixels, thin standard silicon	e2v CCD 44-82 2kx4k, 15-µ pixels, 40-µ DD silicon	MIT/LL 2kx4k, 15-µ pixels, 40 µ high-res. silicon	4x e2v CCD 44-82 2kx4k, 15-µ pixels, 40 µ DD silicon
Main effects	1.3x increase in UVB response; much increased fringing	Red response doubled; much reduced fringing	Red/NIR response nearly doubled; much reduced fringing	Doubled R/NIR response & reduced fringing (TBC)

Table 1: Detector upgrades of optical VLT instruments since 2005

4. RESEARCH AND DEVELOPMENT

4.1 Curved detectors

The conventional optical design of astronomical instruments typically foresees a flat detector and often a field-flattening lens. However, Nature has shown that simpler constructs become possible if the detector (e.g., the retina of the human eye) is curved. Curved detectors would not only simplify optical designs but also enable ones yielding better image quality.

A well-known example is the Schmidt telescope, which features a simple spherical primary but requires a strongly curved detector. Bending photographic glass plates was a delicate procedure but successfully done in most instances. By contrast, electronic detector systems at Schmidt telescopes either do not exist, or only cover a very small fraction of the full field of view, or take advantage of an accidentally curved detector, or consist of several unit detectors arranged on a non-rectilinear grid.

For Extremely Large Telescopes (ELTs) none of these options is viable while the large size of the optics of their instruments adds cost as a further important driver to look into the possibilities of bending semiconductor detectors, too. For the E-ELT, ESO will soon issue a Call for Tender, the main challenge of which will be the small radius of curvature (maximum: 500 mm, goal: 250 mm). More details can be found in Iwert and Delabre (2009).

4.2 Ultra-stable cryostat

The science cases of ESPRESSO for the VLT and CODEX for the E-ELT promote very ambitious scientific goals. For ESPRESSO the top objective is the detection of rocky extrasolar planets through radial velocity measurements. The central goal of CODEX is the direct measurement, from intergalactic absorption lines in quasar spectra, of the acceleration of the expansion of the universe. Both projects require the long-term accuracy and stability of astronomical speedometers to be stepwise improved from the current ~100 cm/s to ~1 cm/s. In terms of positional stability of a detector in an echelle spectrograph, this would correspond to no more than ~100 pm or roughly one silicon atom! The final approval of ESPRESSO and CODEX is still pending. But a careful assessment of candidate technologies, incl. the very important metrology, will require much time. Therefore, ESO is already building an ultra-stable cryostat as a laboratory experiment, which Iwert et al. (2009) describe in more detail.

4.3 Enhancing the UV sensitivity of CCDs

Some years ago, Mingzhi Wei from Lick Observatory kindly provided ESO with a simple but very effective recipe for the removal of spatial inhomogeneities in the UV response of MIT/LL CCDs. The CCDs should for some hours be heated with a tungsten lamp in an O_2-rich atmosphere. Out of curiosity, we applied the same procedure also to other CCDs, mostly from e2v. It turned out that below ~450 nm most, if not all, CCDs that for a long time have been stored under normal atmospheric conditions respond positively. At 300 nm, the typical improvement is by a factor of 1.5. A short subsequent exposure to ambient conditions does not cause a noticeable change. But over many months, the gain in UV sensitivity is mostly lost unless the detector is kept under cryogenic vacuum conditions. By contrast, long storage in cryogenic vacuum is sometimes reported to have the opposite effect.

Interestingly, for the OmegaCAM project some CCDs with UV-bright areas were received. Initially, it was thought that the latter manifest some kind of blemishes. Only after the above procedure had been applied to some of them did it become clear that it was rather the other way round because the UV sensitivity of the 'dark' areas was lifted to roughly the one of the regions with high initial UV sensitivity, which remained about constant. There is no clear explanation yet. But a plausible hypothesis is that H_2O and/or H^+ molecules are adsorbed by the anti-reflection (AR) coating and reduce the latter's effectiveness. In that case, those partly rejected OmegaCAM CCDs might harbor the secret of an extremely effective protective sealing of the AR coating. Deiries et al. (2009) fully illustrate the procedure as well as the results obtained.

5. ADAPTIVE-OPTICS WAVEFRONT SENSORS

5.1 Multi-conjugate Adaptive-optics Demonstrator (MAD) at the VLT

MAD was conceived as a technology explorer (for homogeneous AO corrections over 1-2 arcmin) and so was only operated for a limited period of time (2007/2008). However, scientists who were granted time with the CAMCAO IR camera, which was offered along with MAD, were enthusiastic as became clear during a recent workshop. Thanks to the large aperture of the VLT, IR images competing with the resolution of HST at optical wavelengths were obtained.

The star-oriented (with three Shack-Hartmann wavefront sensors) and the layer-oriented (with two pyramid wavefront sensors) mode of MAD deploy three and two cameras, respectively. Only one set of cameras is operated at any one time. All five cameras are identical and feature e2v CCD39 detectors with Peltier coolers. ESO's FIERA controller was originally specified for 1 Mpixels/s but in this case, thanks to special DSP optimization, performed very much better (80 x 80 pixels, 400 frames/s). With 6-7 e^-, the read noise was still quite acceptable.

5.2 Standard 2nd-generation adaptive-optics wavefront-sensing camera for the VLT

With the Adaptive Optics Facility (AOF), the VLT will substantially expand its high angular-resolution capabilities outside the interferometry domain (VLTI). Three instruments, HAWK-I, MUSE, and SPHERE, will each have their own adaptive-optics (AO) system: GRAAL, GALACSI, and SAXO, respectively. But the wavefront sensor (WFS) systems (more than a dozen in total) will be identical.

Under contract with ESO, e2v developed CCD220, a split-frame transfer L3Vision CCD with 240 x 240 pixels and a maximum frame rate of ~1500 fps. First test results achieved with this device are reported by Feautrier et al. (2009) and, very importantly, include sub-electron read noise.

Because of the very high data rates of up to 14 Mpixel/s in each of 8 channels, the distance between the detector and the controller must not exceed very few centimeters. But within an instrument, space limitations are far more severe than in an off-telescope rack. Therefore, an all new compact, high-speed variant of NGC is being developed (Reyes and Conzelmann 2009). Following the success of OCam, the test camera built for the acceptance tests of CCD220 devices (cf. Feautrier et al. 2009), the VLT AO WFS camera employs the analog electronics of OCam.

5.3 Wavefront sensors for the E-ELT

While on 8-m telescopes adaptive optics can make the difference between good and excellent science (cf., e.g., the recent MAD workshop), ELTs can only beat 8-m telescopes if their AO systems achieve very high performance, i.e. Strehl ratios. Accordingly, ESO has initiated a vigorous R&D program with industrial partners to secure the availability of suitable detectors for the E-ELT (Downing et al. 2009b).

At optical wavelengths, the requirements may be called extreme: Frame rates are determined by the atmospheric coherence time scale and so must reach 1 kHz. In order for the high frame rate to result in high effective time resolution, the signal carry-over from one image to the next must be negligible even at low flux. Similarly, after the end of the integration, the data must be delivered with minimal to the real-time computer controlling the deformable mirror. Since the atmospheric coherence length is not large so that sufficiently close natural reference stars will frequently be faint even with a 42-m telescope, the quantum efficiency must be high especially in the red, where most faint stars have the maximum of their spectral energy distribution. For the same reason, the read noise should not exceed 3 e^-. The temporal sampling and the telescope aperture must be matched by the number of Shack-Hartmann lenslets (or equivalent). In the case of the E-ELT, detailed simulations led to the requirement of 84 x 84 sub-apertures. With sodium-laser reference stars, the finite altitude (~90 km) and thickness (~10 km) of the sodium-rich layer in the high atmosphere causes the Shack-Hartmann spots to suffer elongation, which scales with the aperture of the telescope. On the E-ELT, one Shack-Hartmann lenslet, therefore, needs to have an optical footprint of 20x20 pixels if the sampling is to be adequate. This implies a device with ~3 Mpixels. At 40x40 mm, it will also be large because the need to accurately align the Shack-Hartmann lenslet array with the pixel array implies a pixel size of order 20-24 μ.

The feasibility studies available so far have identified a number of additional challenges. However, they agree in the conclusion that detectors based on CMOS technology stand a fair chance to meet the requirements.

6. SUMMARY

There is a clear trend at ESO towards ever more versatile instruments, in which the roles of the detectors, too, are far more complex than simple picture taking. They are also much more deeply embedded in ambitious operations and calibration schemes. At the same time, the associated relevant detector parameter space (speed, noise, stability, etc.) is growing. The high multiplex of some spectroscopic applications demands multiple detector systems rather than the large mosaics employed by wide-angle imagery.

At the level of optical unit detectors at ESO, the single most important recent advancement has been the substantially increased red QE of thicker devices enabled by much improved depletion technology.

Instruments can now be built around one single type of detector and achieve satisfactory to excellent sensitivity from the onset of the transparency of the atmosphere through the one of silicon.

For the next decade, ESO's optical and IR detector systems will use NGC as their controller. The eventual demise of NGC will coincide with the beginning of E-ELT operations. ASICs seem well positioned (e.g., Dorn et al. 2009, Loose 2009) and eager to take over many of the tasks of conventional general-purpose detector controllers. The more interesting – since still open – question is when customized ASICs will become affordable for ELT-scale facilities.

At DfA2005 (Beletic et al. 2006), one could get convinced that at some point in future, CMOS detectors will in astronomical applications, too, become more important than CCDs (cf. Hoffman, Loose, and Suntharalingam 2005). It was also pointed out (Baade et al. 2005) that at major astronomical observatories the importance of signal (especially wavefront) sensing would grow substantially relative to the more traditional scientific imaging. But only still more recently has it become likely that CMOS devices may actually make their way into optical astronomy through adaptive-optics wavefront sensing. At present, only CMOS detectors seem to stand a chance to support kHz frame rates at low-noise (~ 3 e^-) and be scalable to Megapixel dimensions as required by ELT adaptive-optics applications.

References

Note: For technical reasons, links to DfA2009 papers are to the files with the respective presentations and posters. For the contributions to the proceedings, please go to the program page and click on the name of the presenter.

Baade D., et al., 2004, Kluwer, ASSL, 300, 197

Baade D., et al., 2006, Springer, ASSL, 336, 73

Baade D., 2008, ESO Document No. VLT-TRE-ESO-13660-4578

Baade D., et al., 2009, NGC - ESO's New General Detector Controller, ESO, The Messenger, 136, 20

Beletic J.E., Beletic, J.W., and Amico P. (eds.), 2006, Scientific Detectors for Astronomy 2005, Springer, ASSL, 336

Cumani C., Stegmeier J., 2009, **Software for the New General detector Controller (NGC)**, these proceedings

Deiries S., Downing M., Baade D., 2009, **CCD UV QE Improvement by Gas and Thermal Treatment**, these proceedings

Dorn R., et al., 2009, **SIDECAR ASIC @ ESO**, these proceedings

Downing M., Baade D., Deiries S., Jorden P., 2009a, **Bulk Silicon CCDs, Point Spread Functions, and Photon Transfer Curves: CCD Testing Activities at ESO**, these proceedings

Downing M., Finger G., Baade D., Hubin N., Kolb J., Iwert O., 2009b, **Wavefront Sensors for Adaptive Optics**, these proceedings

Feautrier Ph., et al., 2009, **OCam and CCD220 - World's Fastest and Most Sensitive Astronomical Camera**, these proceedings

Finger G., Dorn R., Eschbaumer S., Ives D., Mehrgan L., Meyer M., Stegmeier J., 2009, *Detector Projects at ESO* **(Infrared),** these proceedings

Hoffman A., Loose M., Suntharalingam V., 2005, Springer, ASSL, 336, 377

Iwert O., et al., 2006, Springer, ASSL, 336, 345

Iwert O., Delabre B., 2009, **The Challenge of Highly Curved Monolithic Imaging Detectors**, these proceedings

Iwert O., Gullieuszik M., Manescau A., Dekker H., Lizon J.L., 2009, **Ultrastable Operation of CCDs for High Resolution Spectrographs**, these proceedings

Loose M., 2009, **Architecture and Operations Concept for the Advanced Camera for Surveys Repair**, these proceedings

Meyer M., et al., 2009, **Detector Data Acquisition Hardware Designs and Features of NGC (New General Detector Controller)**, these proceedings

Reiss R., Deiries S., Lizon J.L., Rupprecht G., 2009, **The MUSE Detector System**, these proceedings

Reyes J., Conzelmann R., 2009, **ESO AO Wavefront Sensor Camera**, these proceedings