GRAVITY detector systems

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ABSTRACT

GRAVITY is a second generation instrument for the VLT Interferometer, designed to enhance the near-infrared astrometric and spectro-imaging capabilities of VLTI. It will combine the AO corrected beams of the four VLT telescopes. The GRAVITY instrument uses a total of five eAPD detectors, four of which are for wavefront sensing and one for the Fringe tracker. In addition two Hawaii2RG are used, one for the acquisition camera and one for the spectrometer. A compact bath cryostat is used for each WFS unit, one for each of the VLT Unit Telescopes. Both Hawaii2RG detectors have a cutoff wavelength of 2.5 microns. A new and unique element of GRAVITY is the use of infrared wavefront sensors. For this reason SELEX-Galileo has developed a new high speed avalanche photo diode detector for ESO. The SAPHIRA detector, which stands for Selex Avalanche Photodiodes for Highspeed Infra Red Applications, has been already evaluated by ESO. At a frame rate of 1 KHz, a read noise of less than one electron can be demonstrated. A more detailed presentation about the performance of the SPAHIRA detector will be given at this conference [1]. Each SAPHIRA detector is installed in an LN2 bath cryostat. The detector stage, filter wheel and optics are mounted on the cold plate of the LN2 vessel and enclosed by a radiation shield. All seven detector systems are controlled and read out by the standard ESO NGC controller. The NGC is a controller platform which can be adapted and customized for all infrared and optical detectors. This paper will discuss specific controller modifications implemented to meet the special requirements of the GRAVITY detector systems and give an overview of the GRAVITY detector systems and their performance.

Keywords: IR detectors, CCD detectors, eAPD, detector controller, near-infrared

1. INTRODUCTION

GRAVITY is a second generation adaptive optics assisted, near-infrared VLTI instrument for precision narrow-angle astrometry and interferometric phase referenced imaging of faint objects. Figure 1 shows an overview of the GRAVITY instrument[2]. The beam combiner instrument (bottom right) is located in the VLTI laboratory. The infrared wavefront-sensors (bottom left) are mounted to each of the four UTs. The laser metrology is launched from the beam-combiner and is detected at each UT/AT (top middle).

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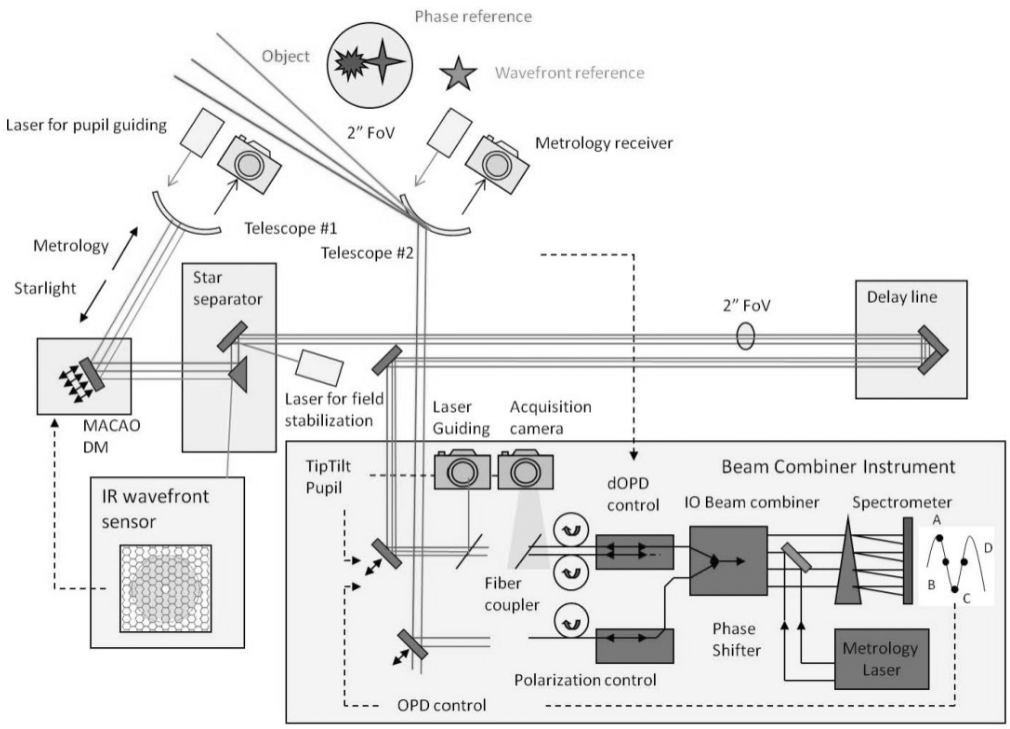

Figure 1 Working principle of GRAVITY

2. DETECTOR SUBSYSTEMS OF GRAVITY

The GRAVITY instrument comprises a total of seven near-infrared detector arrays: two Hawaii2RG detectors and five SELEX (SAPHIRA) eAPD detectors. Hawaii-2RG arrays with 2048 x 2048 pixels are used in the science spectrometer, and acquisition camera. One SAPHIRA eAPD detector is used for the Fringe Tracker subsystem and four are used for the wavefront sensors. All detector systems, including the detector controller NGC, are supplied by ESO. The GRAVITY instrument has 2 spectrometers[5]: one for the science object and one for the fringe tracker object. For the science spectrometer a Hawaii2RG detector with a useful area of 620x2048 pixels and cutoff wavelength of 2.5 µm is used. One SAPHIRA eAPD detector with 320x256 pixels is used for the Fringe tracker.

2.1 Wavefront sensors

The GRAVITY wavefront sensor (WFS) is part of the 2nd generation VLTI instrument GRAVITY [6]. The GRAVITY WFS provides a complete adaptive optics system, which can be generally used at the VLT interferometer (VLTI) due to its stand-alone character. It adds near-infrared (NIR) wavefront sensing to the VLTI and as such complements the available visible wavefront sensing MACAO systems [7]. Table 1 shows defined parameters for the WFS systems.

Table 1 GRAVITY WFS parameters

Parameter	Value
Spectral range	H and K-band (1.4-2.4 um)
Frame size	72 x 72 pixels
Frame rate for in windows mode	500 fps
Frame rate in full frame mode	1000 fps
Number of sub-apertures (lenslet mask)	9x9
Number of detector pixels per sub-apertures	8x8 pixel
Read noise	< 3 erms

For windowed readout, the window sizes have to be a multiple of 32 in the “x” direction, and can have any size in the “y” direction. Thus always 96 x72 pixels will be readout.
The Wavefront Sensor uses a single SAPHIRA detector for all four beams. The detector is controlled and read by the ESO detector controller, NGC. Figure 2 shows the NGC DCS (Detector Control Software) and two real-time displays (RTD). The picture on the right side shows the image received through the SPARTA system (ESO real-time system for AO application) when a lenslet is used in front of the SAPHIRA detector. Figure 3 shows the linearity of the SAPHIRA detector versus time at different flux levels generated by varying the blackbody temperature. The raw signal versus time is strongly nonlinear below 50 ms but subtracting corresponding dark frames from frames exposed to the radiation emitted by the blackbody at temperatures of 80 C and 90C yields a linear time dependence. Therefore, empty sky or dark frames have always to be subtracted before processing the image.

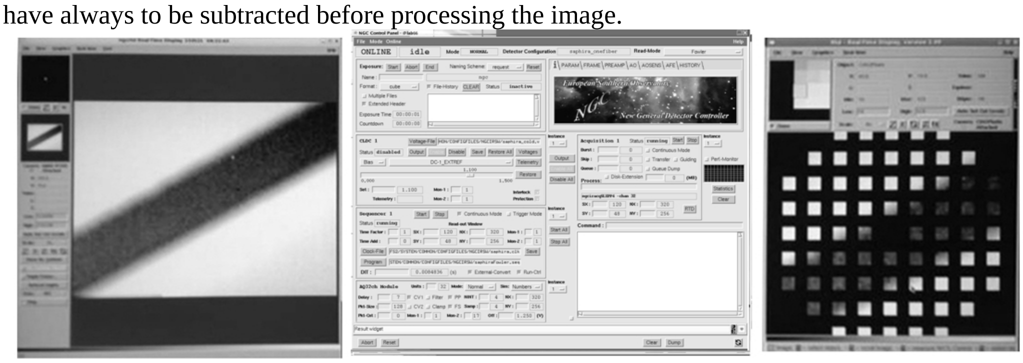
Figure 2 (left) NGC-RTD, (mid) NGC DCS GUI, (right) SPARTA RTD

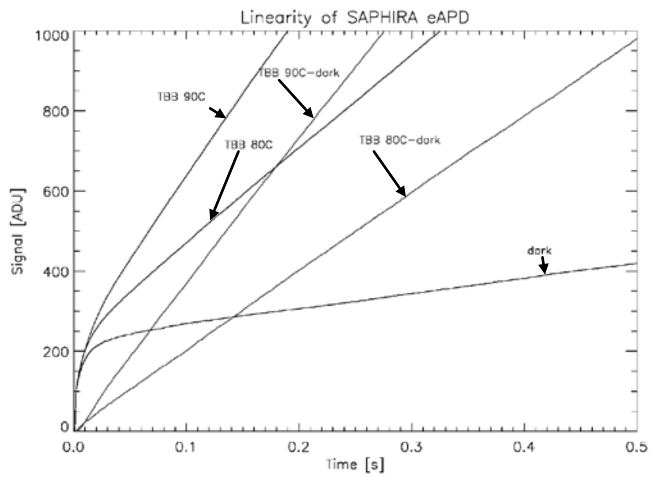

Figure 3 Linearity vs. temperature of the WFS SAPHIRA detector

2.2 WFS cryostat

The design is based on the ESO “interferometry” bath cryostat. This is a two tank cryostat which has already been used for LISA, FINITO and IRIS. The detector stage, filter wheel and optics are mounted on the cold plate of the LN2 vessel and enclosed by a radiation shield. The version used for this application is closer to the SPHERE cryostat which has the optical axis perpendicular to the cryostat main axis. The two tank configuration allows the detector to be cooled close to the liquid nitrogen temperature. The upper tank is mainly used to cool the radiation shield and the pre-detector optic system, while the detector system is cooled by the lower tank. This allows obtaining a stable temperature on the detector.

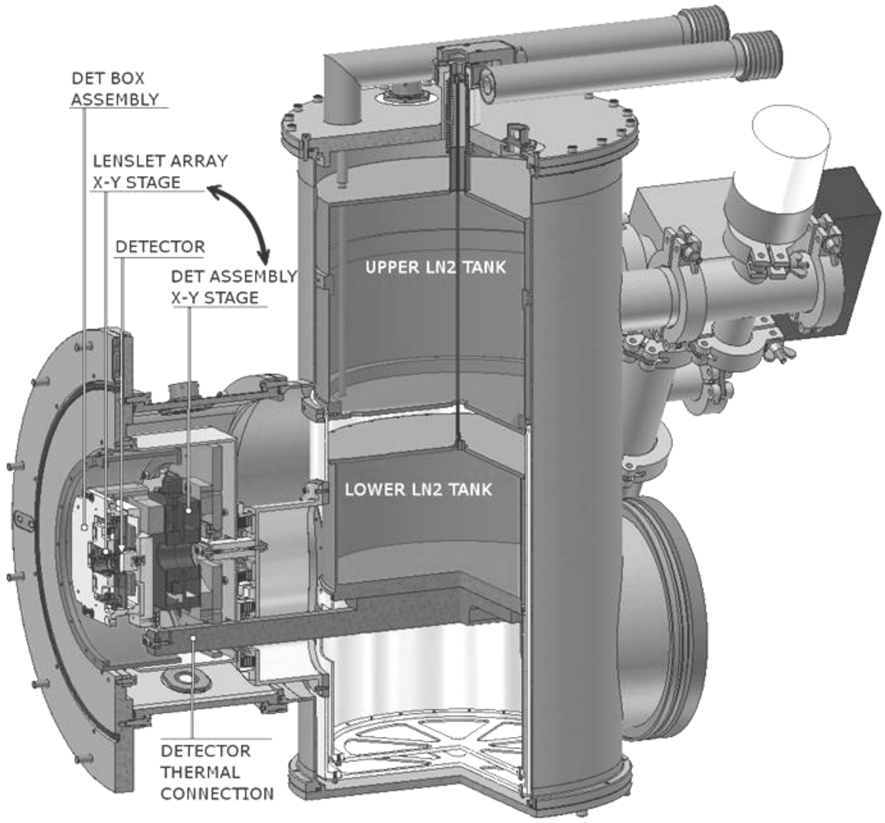

Figure 4 GRAVITY WFS cryostat

2.3 Pulse Tube Cryo-Cooler

To obtain the best detector performance the requirement was to operate the SAPHIRA LPE detector at 45 Kelvin. Due the location of the system in the Coude and Interferometry lab the cooler had to be vibration free. Hence a pulse-tube cooler was initiated by both Max-Planck institutes and ESO [10]. The University of Giessen has successfully developed such as cooler which has its warm end heat sinked to the optical bench of the instrument which is at a temperature of T=80K and the cold is heat sinked to the detector at T=40K. Extensive tests were done in the final environment of the beam combiner cryostat and a detector temperature of 40K at a cooling load of 2.5W could be achieved. The final design is shown in Figure 5.

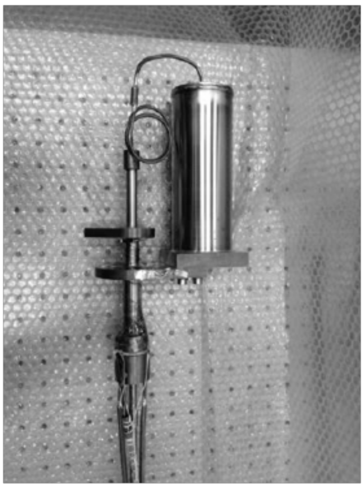

Figure 5 Pulse Tube Cryo-Cooler

2.4 SAPHIRA detector mount

A new mechanical setup has been designed to be used as the ESO standard setup for applications needing a single SAPHIRA detector. The result is a very compact design: the preamplifier flex-rigid board equipped with the detector socket, the intermediate connectors for the light-tight radiation shield feed-through and the vacuum connector.

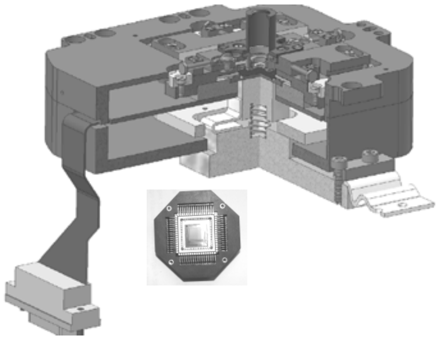

Figure 6 SAPHIRA mount (the small photograph shows the detector in its socket)

In order to readout the SAPHIRA detector at 5 MHz a high speed symmetric preamplifier running at cryogenic temperature has been designed (shown in Figure 7). The main heat source in the vicinity of the detector is the preamplifier which puts a certain heat load on the detector. The maximum power dissipation of the preamplifier (consisting of 64 CMOS operational amplifiers, 2 per channel) is about 2.56 W. In comparison, the power dissipation of the detector is negligible. It is important to redirect the major fraction of the heat flow to the instrument by a thermal clamp of the detector cables and proper heat sinking of the preamplifier box. In order to ensure that the heat dissipated by the opamps does not heat the detector but is heatsinked to the instrument a cryogenic board has been designed with extra thermal layers to redirect the heat away from the detector and straight to the cold points. Figure 7 shows the layout of the board highlighting the discrete elements and the thermal layer.

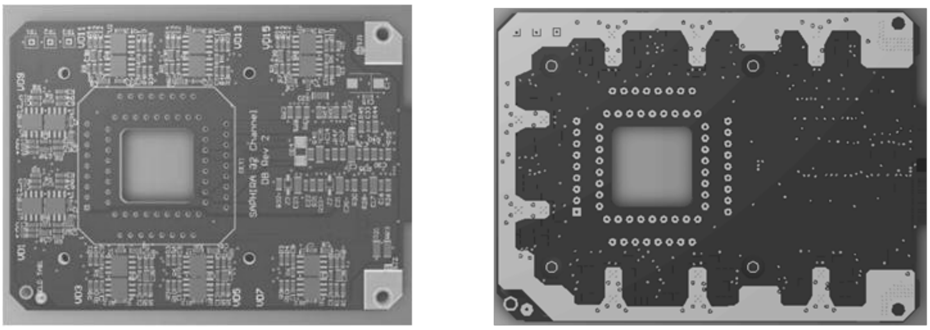

Figure 7 SAPHIRA detector preamp board. Right picture internal thermal layer

3. FRINGE TRACKER

The GRAVITY fringe tracking spectrometer with 6 baselines of the 4 telescopes, 4 readings for the ABCD algorithm to determine the fringe position and 2 polarization, and produces 48 spectra . All spectra have to be read at frame rate of at least 1 KHz. The SAPHIRA detector is used for the fringe tracker subsystem. The detector is controlled and read by the ESO detector controller, NGC. Using the SAPHIRA windowing features we are able to read out 24 windows each having 32x1 pixels in 5 µs. For frame rates of 2 KHz heavy multiple sampling techniques can be applied with up to 50 Fowler pairs to reduce the readout noise. Figure 8 shows the design of the GRAVITY fringe tracker subsystem.

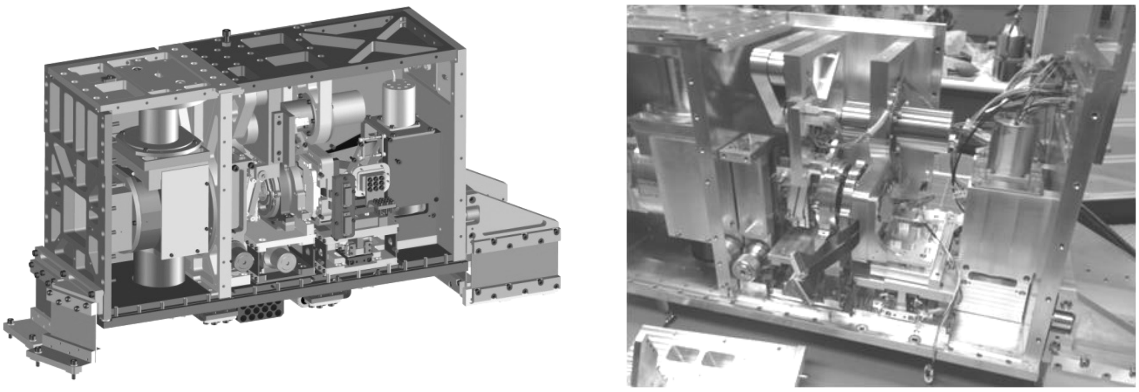

Figure 8 GRAVITY Fringe Tracker subsystem

To determine phase and amplitude a fringe measurement of 4 positions shifted by 90 degrees needed to be performed (shown in Figure 9).

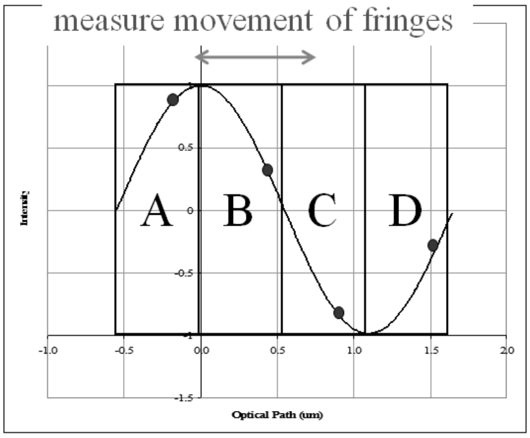

Figure 9 Measure movement of fringes

For more detailed information see“The GRAVITY fringe tracking system” [3], SPIE paper 9146-57.
The APD gain of the SAPHIRA detector can be set by the bias voltage across the diode. Figure 10 shows the relation between the bias voltage and the APD gain.

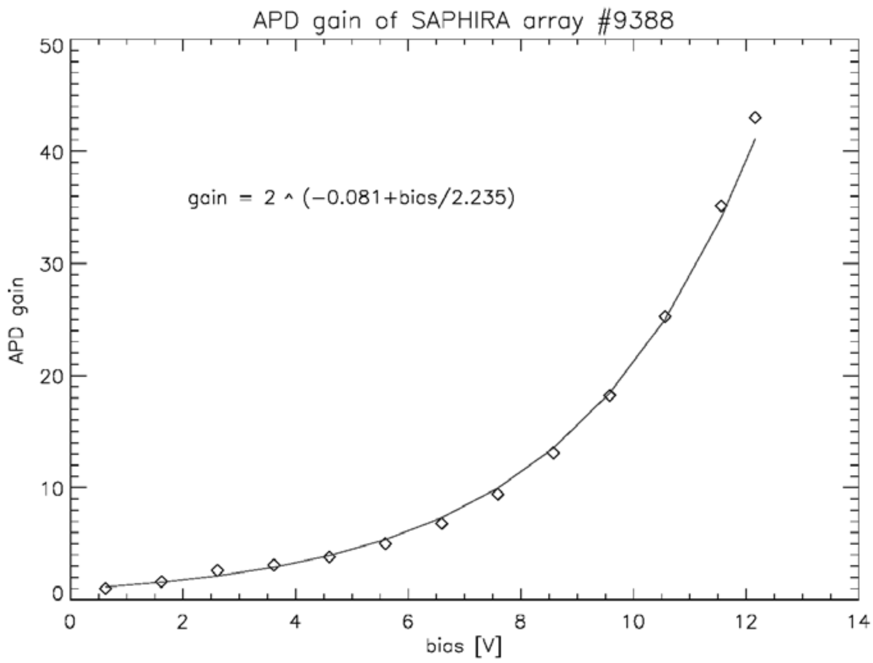

Figure 10 APD gain of the Fringe Tracker SAPHIRA detector

The QE of the SAPHIRA LPE array in K-band is 82% and in H-band 62% when the detector is operated at 40 K. When the detector is operated at T=80 K then the QE in K-band decreases slightly to 75% and in H-band to 45% (shown in Figure 11).

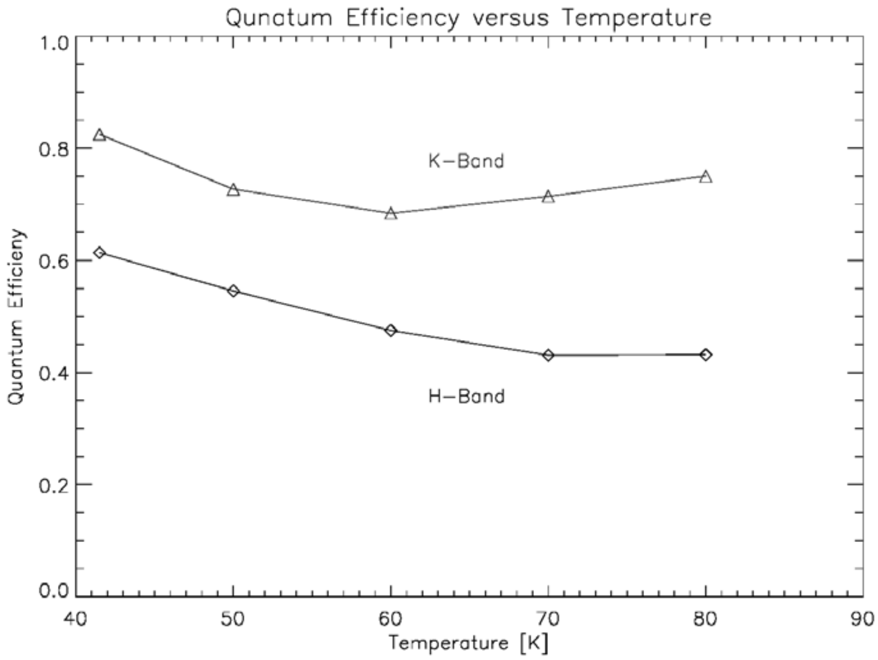

Figure 11 QE vs. detector temperature of the Fringe Tracker SAPHIRA detector

The cosmetic quality of the SAPHIRA LPE array at high APD gain gets worse. The left picture of Figure 12 shows the detector at a bias of 1.5 V and the right one at a bias of 12 V.

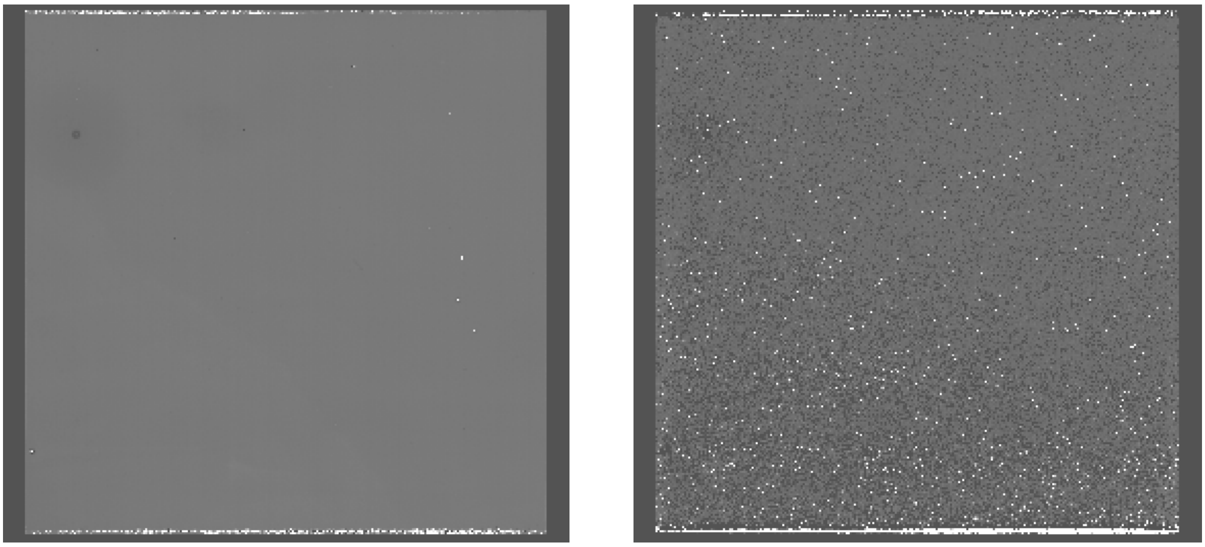

Figure 12 Cosmetic of the Fringe Tracker SAPHIRA LPE detector at 80K and different APD gain

In order to reduce the readout noise the Fowler readout technique has been used. This achieves 0.8 e-rms for DCS of a full frame and 0.26 e-rms with 16 Fowler pairs for 96x72 pixels could be obtained. Figure 13 shows the dependency of the read noise on the number of Fowler pairs at different detector temperatures. Full frame noise histogram of Fowler vs. DCS is shown Figure 14. The dependence of signal versus flux at a fixed integration time at the maximum APD gain is shown in Figure 15.

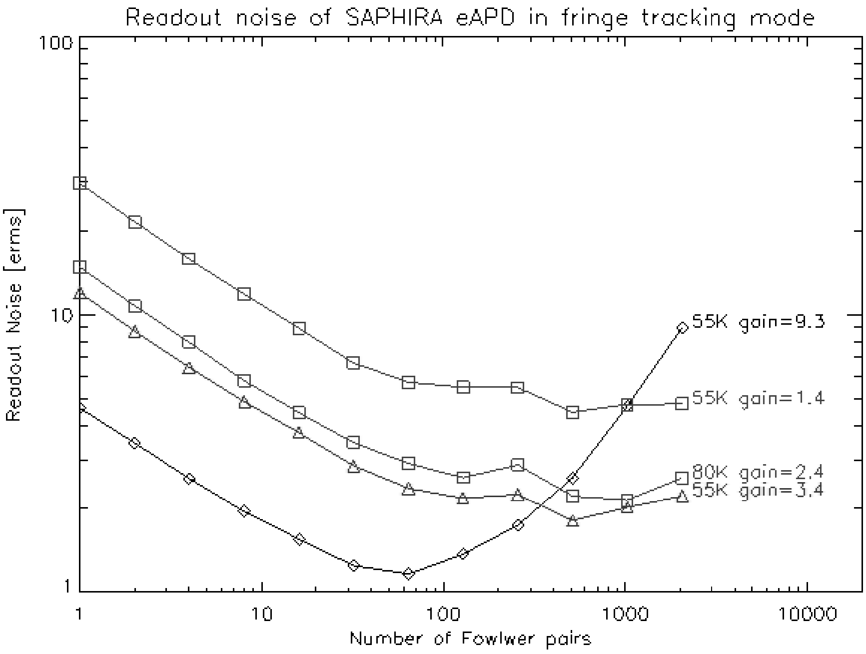

Figure 13 Number of fowler pairs for fringe tracker

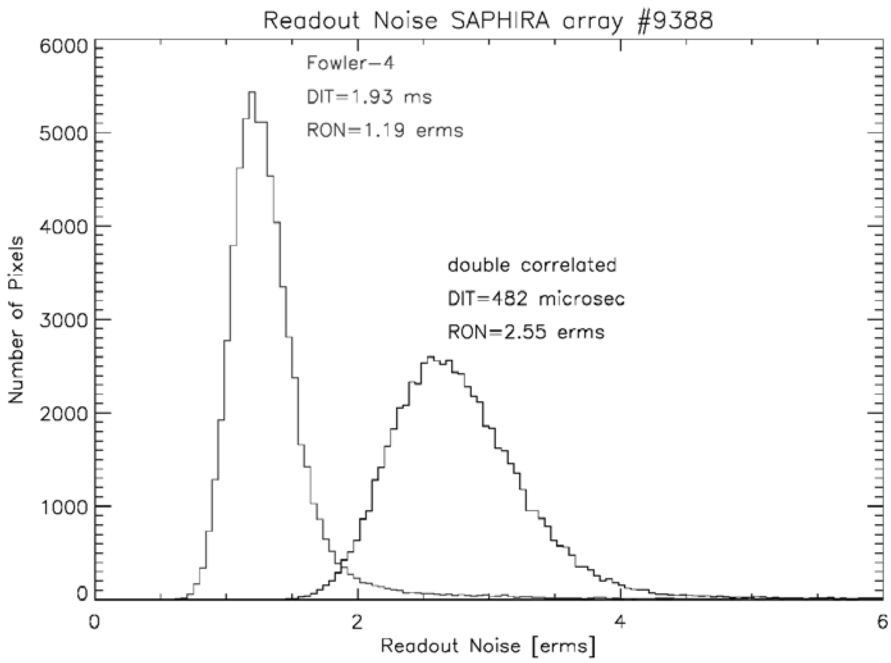

Figure 14 Fowler vs. double noise histogram of the Fringe Tracker SAPHIRA detector

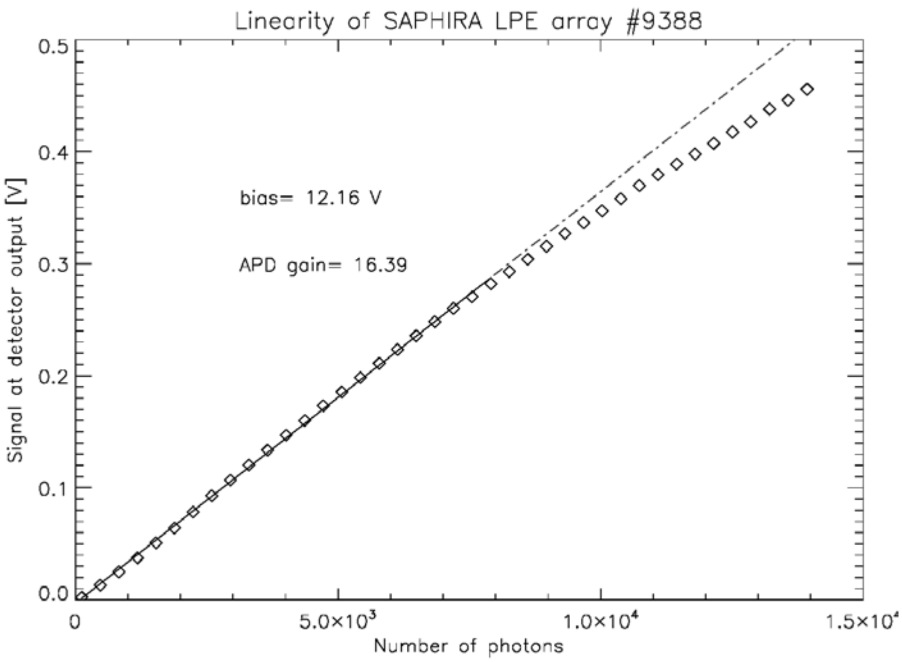

Figure 15 Linearity with APD gain of the Fringe Tracker SAPHIRA detector

First fringes have been obtained. See Figure 15, with the GRAVITY whilst cooling the SAPHIRA eAPD array to a temperature of 48 K with a small Sterling type pulse tube closed cycle.

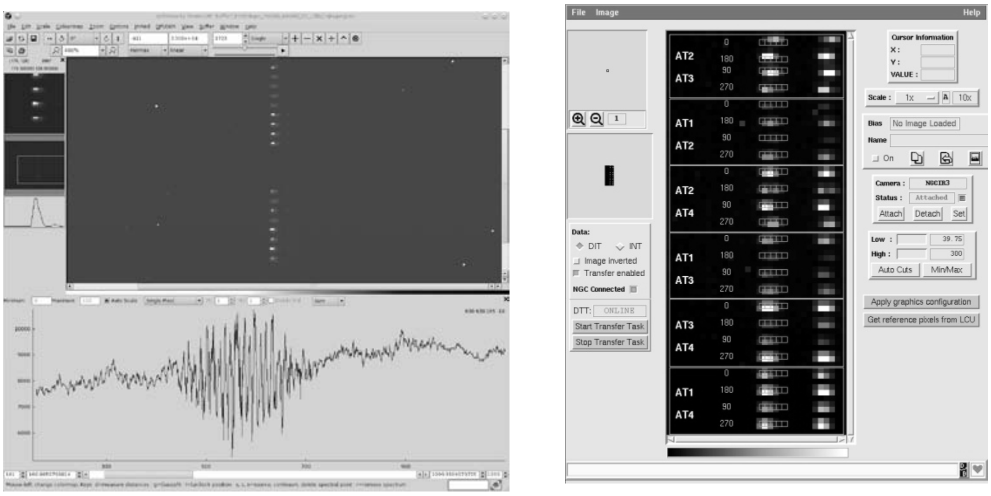

Figure 16 First fringes obtain with the GRAVITY fringe tracker

4. SCIENCE SPECTROMETER

The Hawaii-2RG array will receive the 48 spectrally dispersed signals from the GRAVITY science beam combiner, spread over 5 to 512 pixels (depending on the spectral resolution mode), with integration times from 0.1 to 100 seconds. A Hawaii2RG array has 2048x2048 pixels with size of pixel of 18x18 um^2, but maximum 640x2048 pixels are used.

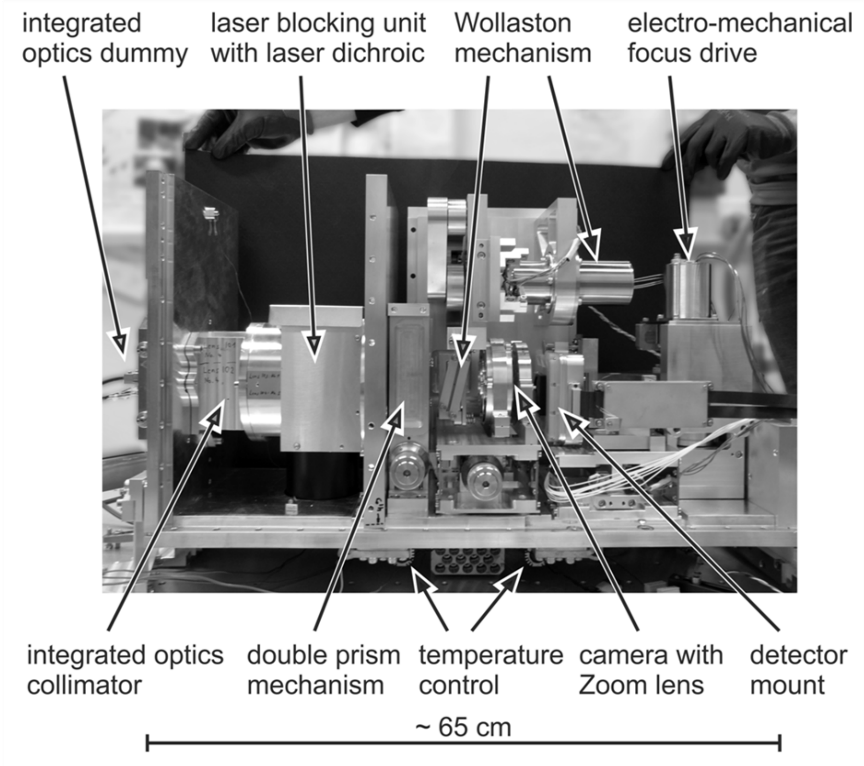

Figure 17 GRAVITY Science Spectrometer

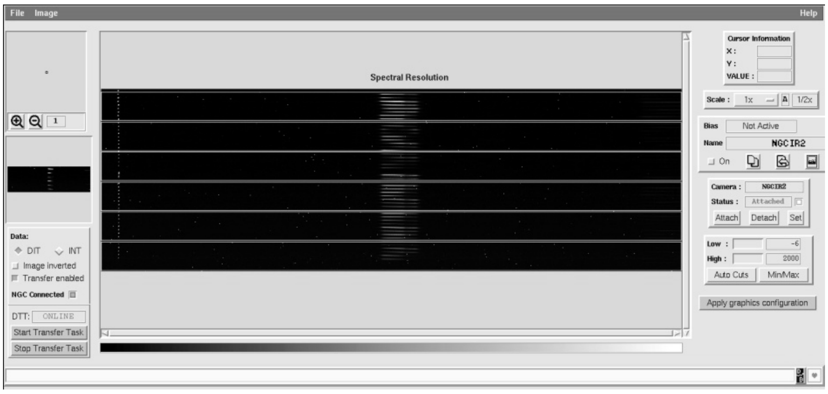

Figure 18 Spectra of science spectrometer on the Hawaii2RG

5. ACQUISITION AND GUIDING CAMERA

The GRAVITY Acquisition Camera is designed to monitor and provide field and pupil images, a Shack-Hartmann wavefront sensor image, and a pupil tracker image for all four telescopes. The field image is used for acquisition and to control low frequency tip/tilt drifts. It is the only GRAVITY subsystem that has access to the four telescope images at the beam combiner.

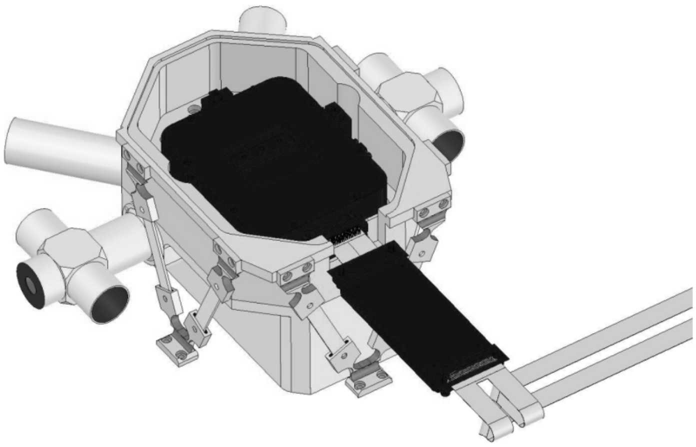
Figure 19 Acquisition camera detector and beam analyzer cold support structure

The following requirements are defined on the detector:

- Wavelength range: K-band
- Number of pixels for acquisition: 160 x 160 pixels •
- Number of pixels for guiding: 10 x 10 pixels •
- Frame rate for acquisition: 1fps •
- Frame rate for stabilization: 100 fps •
- Read noise: 11 erms

6. TWO HAWAII2RG DETECTORS FOR THE GRAVITY SUBSYSTEMS

For both GRAVITY subsystems, Acquisition-Guiding Camera and Science Spectrometer, Hawaii2RG detectors have been used. Hawaii2RG MBE is grown on CdZnTe substrates and has 2Kx2K with the pixel size of 18 µm. Reference pixel subtraction and 32 parallel video outputs are additional features of this detector. As shown on Figure 21 ESO standard setup for the Hawaii2RG detector has been used for the GRAVITY susbsystems.

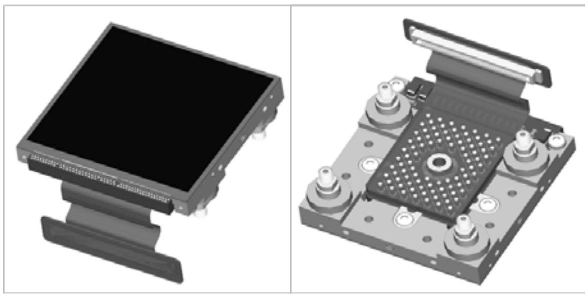

Figure 20 Hawaii2RG IR array

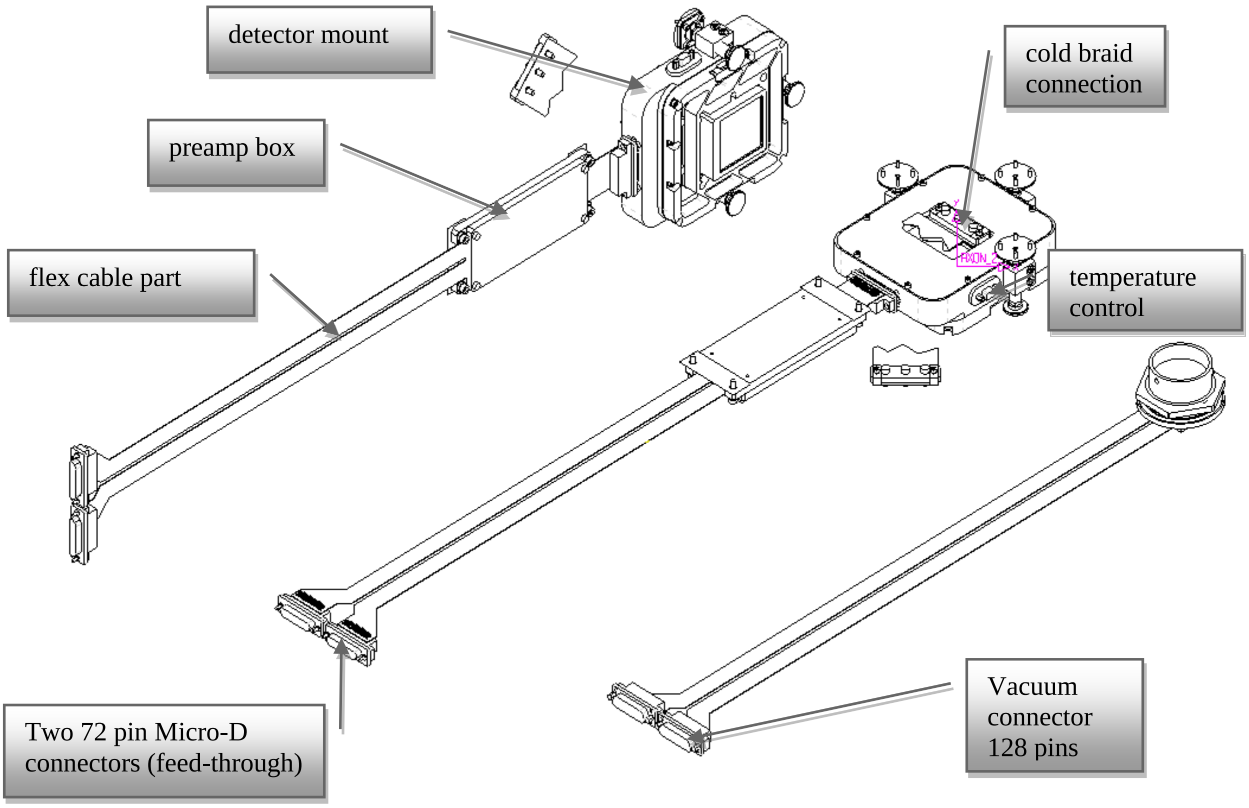

Figure 21 ESO standard setup for the HAwaii2RG detector

For the verification of the GRAVITY Hawaii2RG detectors the ESO IR mosaic test facility has been used. This makes it possible for us to test both arrays at the same time by using a GL Scientific detector mount (shown on Figure 22). Figure 23 shows flat field images of both GRAVITY Hawaii2RG detectors in K-band. This is the difference of two flat fields with a blackbody at 380C and 300C. The left picture is the detector array used for the Acquisition Camera (with SN 16774) and the right one is used for the Science Spectrometer (with SN 16775). Pixels inside the rectangle were used for pixel transfer function and efficiency.

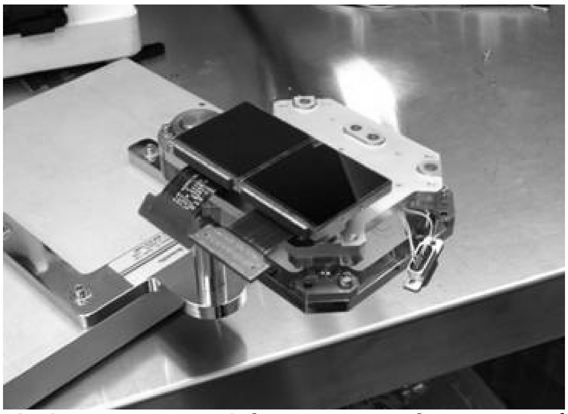

Figure 22 GRAVITY Hawaii2RG detectors mounted on JL mount for testing

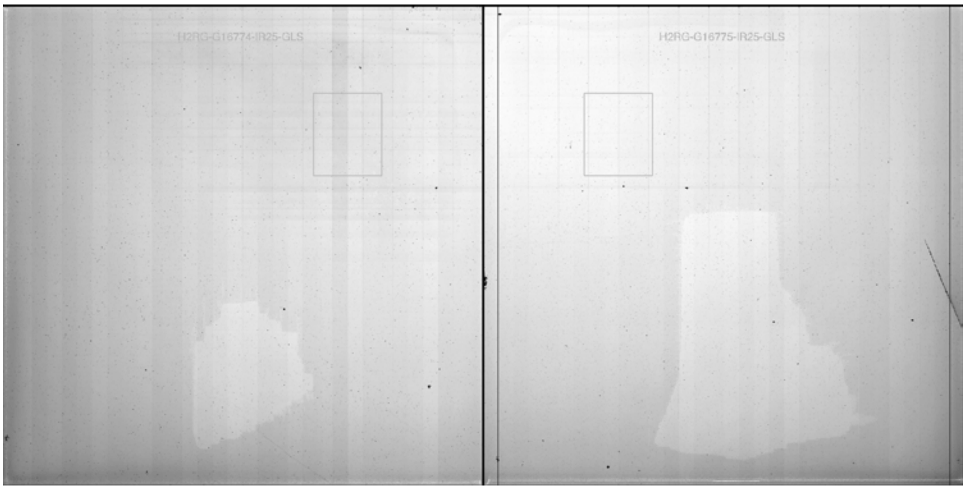

Figure 23 Flatfield of both Hawaii2RG arrays in K-band

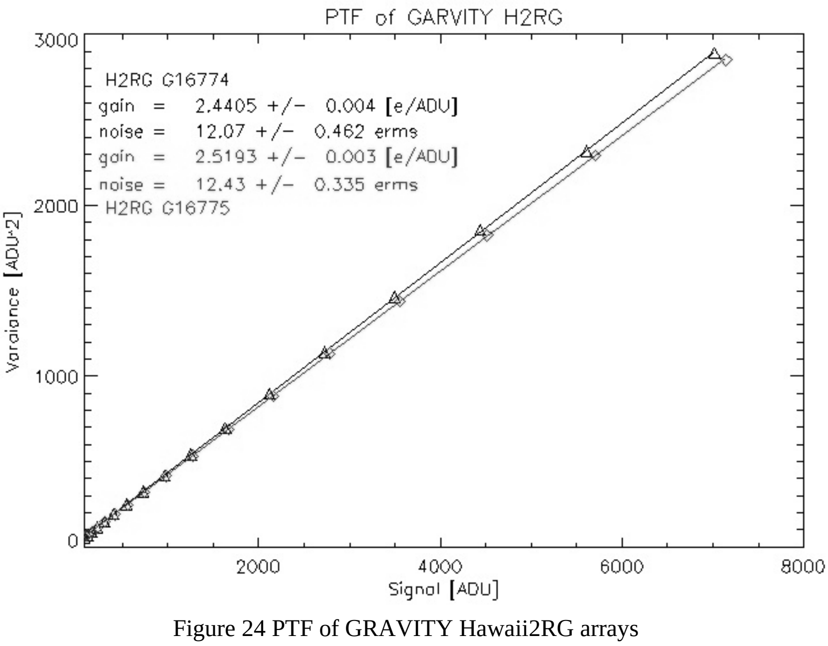

Figure 24 PTF of GRAVITY Hawaii2RG arrays

The widespread “noise squared versus signal” method used to obtain the conversion gain overestimates the nodal capacitance of the detector pixel by more than 20% for infrared arrays and by more than 100% for Si-PIN diode arrays. This is because the method does not take into account the capacitive coupling between neighboring pixels. A simple technique, developed by G. Finger [8], to measure the nodal capacitance directly by comparing the voltage change of an external calibrated capacitor to the sum of the voltage change of all pixels yields a correction factor for the conversion gain obtained with the variance versus signal method of 1.26. Multiplication of the measured value (shown in Figure 24) with the factor of 1.26 give us the real conversion gain values of both GRAVITY arrays:

PTF of the Acquisition Camera detector: 3.5 µV/e

PTF of the Science Spectrometer detector: 3.3 µV/e

Figure 25 shows readout noise versus number of nondestructive readouts for Fowler sampling of both GRAVITY Hawaii2RG detectors.

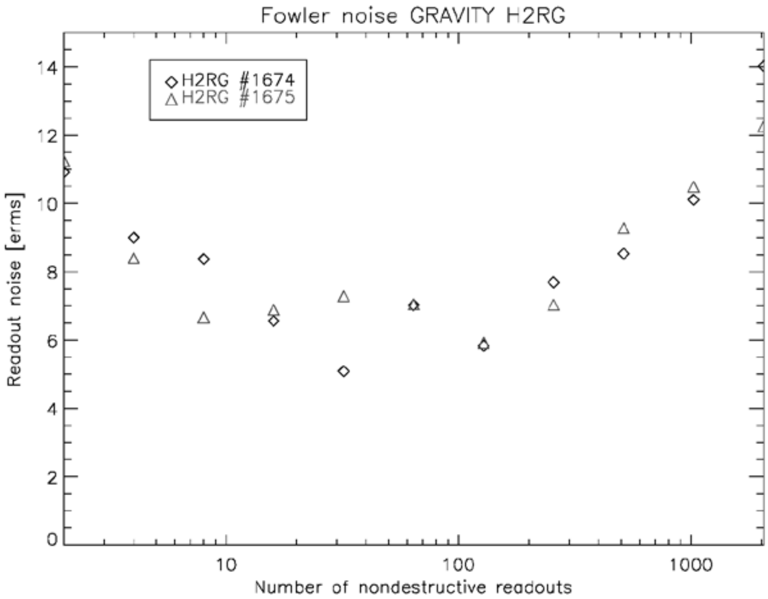

Figure 25 Readout noise versus number of nondestructive readouts for Fowler sampling

7. SAPHIRA DETECTOR BASELINE FOR THE GRAVITY

Up-to-now the baseline for all five GRAVITY SAPHIRA detectors was the SAPHIRA LPE detector with pulse-tube cryo-cooler operating at 45 Kelvin. Even at low operation temperature (45 Kelvin) and at high APD gain the cosmetics of the LPE array is poor. The left picture of Figure 26 shows the cosmetics of the LPE array running at 45 Kelvin with an APD gain of 16.6 and the right picture shows the MOVPE array running at 85 Kelvin and APD gain 28.2. As can be seen even at higher APD gain the cosmetic quality of the MOVPE detector is extremely good and has only 18 bad pixels at high APD gain. For more detailed information see SPIE paper of Gert Finger [1]. Using the SAPHIRA MOVPE detector will also clearly simplify the system by removing the Pulse Tube cooler from the structure which leads to easier system maintenance due of less mechanical parts. ESO together with the GRAVITY consortia are discussing whether to upgrade all LPE arrays to MOVPE devices.

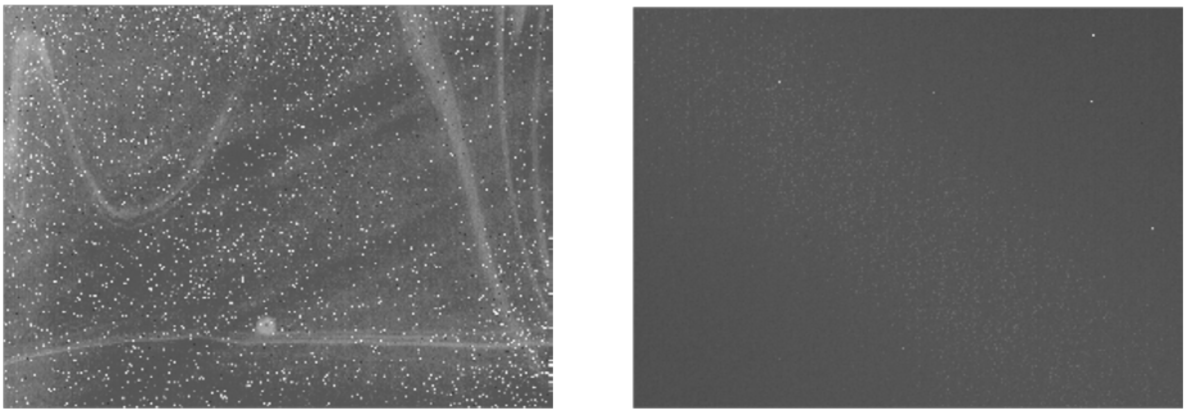

Figure 26 Left SAPHIRA- LPE and MOVPE array

8. ESO DETECTOR CONTROL SYSTEM NGC

The data acquisition system of all GRAVITY detector arrays is the ESO common readout electronics NGC. The ESO NGC, New General common Controller, had its first light at the ESO Paranal Observatory in 2012 The controller has evolved over three decades from previous controller generations, namely the ESO IRACE and FIERA detector controllers. NGC is a controller platform which can be adapted and customized for all infrared and optical detectors. Various ESO instruments already use the NGC. Since NGC runs all new detector systems for ESO instruments, a uniform platform is available at the observatory which facilitates operation and maintenance. Figure 27 shows an overview of NGC systems. For IR detector like Hawaii2RG and SAPHIRA arrays we use a compact version of the NGC system shown in Figure 28. This NGC system contains one basic module generating all required clocks and biases and one 32-channel video board. The front-end electronics interface is via 2.5 Gbit/s fiber interface connected to the back-end. The data capturing module is a PCIe based module with a data throughput of 20 Gbit/s. Therefore this module can be used to control and data capture from two front-end electronics simultaneously. The NGC controller is a modular, customizable system. Just like “Lego” blocks we can combine different modules to cover our needs.

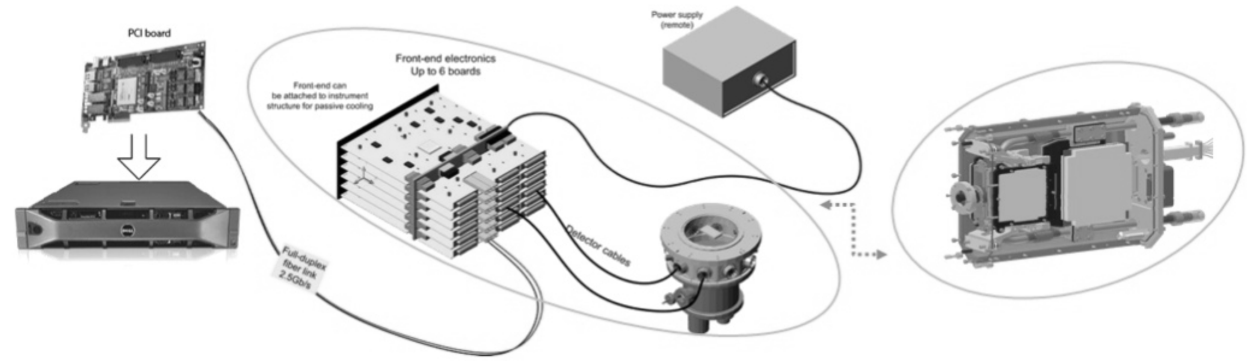

Figure 27 Scheme of the NGC system

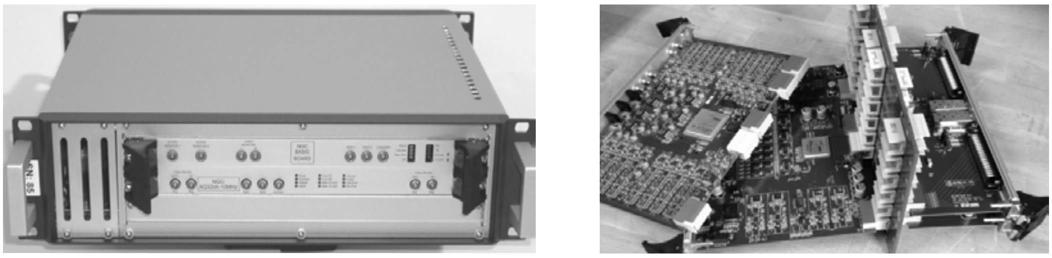

Figure 28 NGC system to readout a SAPHIRA IR array

8.1 ESO instruments using the NGC

The NGC already had its first light at the VLT Telescope in Chile. Various ESO instruments already use the NGC. Figure 29 shows symbols of instruments which already use the NGC. An instrument like MUSE reads out 24 CCDs simultaneously and SPHERE uses several different types of detectors like the Hawaii2RG and the Hawaii1 infrared detectors, ZIMPOL CCD and adaptive optics CCD220. Recently we achieved the best performance with the SAPHIRA MOVPE eAPD detector. The ESPRESSO instrument, with the largest clock capacitance ever handled by a controller, had its first light with the NGC.

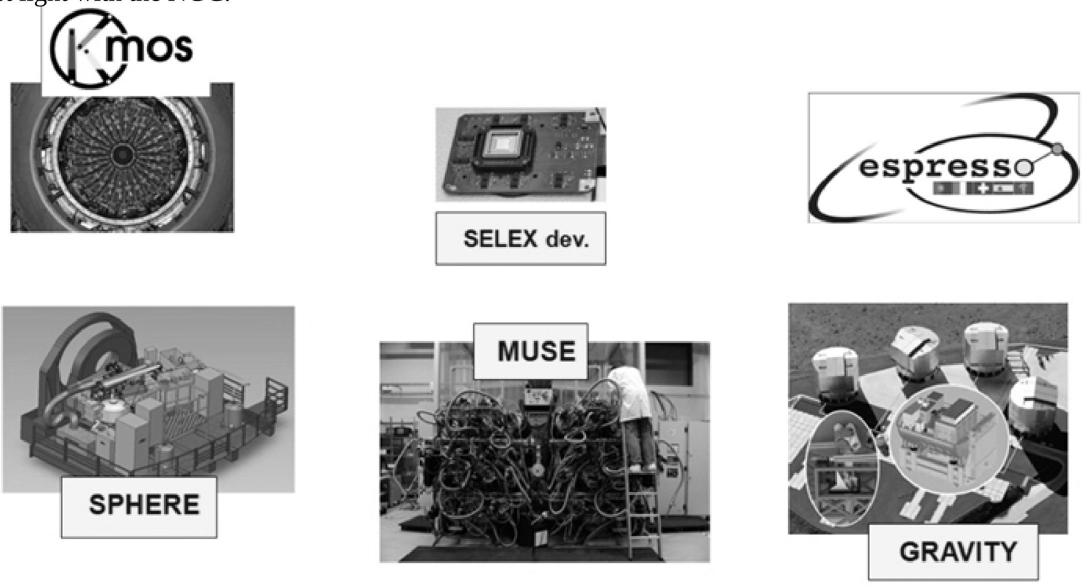

Figure 29 Various ESO instruments using the NGC

8.2 Requirements for vibration free systems

Since the WFS subsystems of GRAVITY has to be used in the VLTI tunnel very strict vibrational requirements need to be met. Thus the Thermacore Company was tasked to approve and re-design a fanless electronics housing. A new concept, based on conduction and liquid cooling, has been proposed, investigated via simulation and finally tested as a prototype. The NGC electronics modules, with components on both sides, are mounted on conduction cards. Thick gap filler type TIM (thermal interface material) has been used to connect the boards to the conduction cards made out of Aluminum. The conduction cards are thermally interlocked with the housing by the use of wedgelocks. Figure 30 shows the 3D-model operational NGC fanless system.

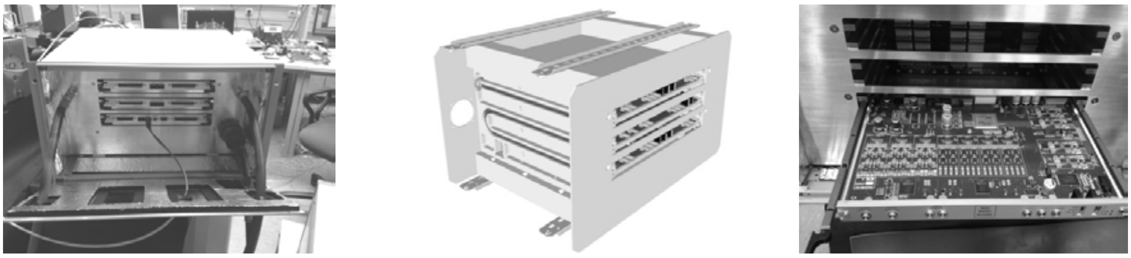

Figure 30 NGC fanless housing

9. CONCLUSIONS

The GRAVITY instrument is being integrated and tested at MPIA in Heidelberg and MPE in Garching. The main structure containing the science Spectrometer, Fringe Tracker, and Acquisition Camera is at the MPE and all four WFS subsystems will be integrated at the MPIA in Heidelberg. One of the WFS systems is already in operation and the other three will follow within the next 12 month.
With eAPDs near-infrared detectors sub-electron noise is a reality at frame rates of one KHz.
We are able to easily detect flux of 1 photon/exposure/pixel for DIT of 1 ms.
RON:

- ✓ 0.8 erms for DCS of full frame
- ✓ 0.26 erms with 16 Fowler pairs for 96x72 pixels.

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