## Title
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# State of the art IR cameras for wavefront sensing using e-APD MCT arrays

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**ABSTRACT**

The recent discovery of electron initiated avalanche photodiodes (e-APDs) using mercury cadmium telluride semiconductor materials has permitted a significant advance in short-wave infrared imaging. In the visible spectrum, electron-multiplying charge-coupled devices (EMCCDs) improved imaging techniques—especially in the life sciences. And yet, no significant breakthroughs have been made in infrared imagery since the hybridization of III-V or II-VI semiconductors with low bandgap on complementary metal-oxide semiconductor (CMOS) read-out integrated circuits (ROICs).
In 2012, Philippe Feautrier *et al.*[1] and Gert Finger *et al.* [2] of the European Southern Observatory (ESO; Garching, Germany) reported successful hybridization of HgCdTe e-APDs on CMOS ROICs with a significant number of pixels (320 × 256). Feautrier *et al.* [3] also reported the use of a Sofradir/CEA-LETI APD array on the ESO Very Large Telescope Interferometer (VLTI), called RAPID, demonstrating for the first time the successful operation of this technology in a representative environment.
First Light Imaging [4] is the first commercial company to make e-APD infrared array technology available in its C-RED One camera. Using a 320 × 256, 2.5 µm cutoff wavelength HgCdTe e-APD array deeply cooled to 80 K with a high-reliability pulse-tube cryocooler (mean-time between failure or MTBF of approximately 90,000 hours), the camera has a high readout speed of 3500 frames/s (full frame) while exhibiting a readout noise below one electron—thanks to the APD gain in the range of 1 to 60.
This paper reports on the results of the Sofradir/CEA-LETI RAPID program [5] and on the development of the C-RED one infrared camera from First Light Imaging based of the SELEX SAPHIRA detector [6]. The interest of Short Wavelengths InfrRed (SWIR) e-APD versus more classical HgCdTe arrays as infrared tilt sensors or pyramid wavefront sensor like what is currently developed at Keck Observatory is also discussed in this paper.

**Keywords:** Adaptive optics, EMCCD, Avalanche photodiodes, APD, HgCdTe, SAPHIRA, SELEX, wavefront sensor, infrared sub-electron noise, life sciences, bio-imaging.

## 1. INTRODUCTION

Developed by First Light Imaging and based on the SAPHIRA detector developed by Selex for ESO, the C-RED ONE infrared camera is opening a new era in terms of sensitivity and speed in the SWIR scientific cameras domain and is particularly suited for infrared wavefront sensing as low order (tip-tilt-focus) sensors with LGS AO systems or as high order wavefront sensors with NGS AO systems (e.g. exoplanet science). This is in strong contrast to what is observed in APDs made out of III-V material or Si, which requires high inverse bias and have typical noise factors of F~4-5 for III-V

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semi-conductors and F~2-3 for Si respectively. These exceptional characteristics of HgCdTe APDs are due to a nearly exclusive impaction ionization of the electrons, why these devices have been called electron avalanche photodiodes, e-APDs [7]. These results have inspired a large effort in developing focal plan arrays using HgCdTe APDs for low photon number applications such as active imaging in the range gated mode (2D) and/or with direct time of flight detection (TOF) (3D) and, more recently, passive imaging for infrared wave front correction and fringe tracking in astronomical observations. C-RED is using the SAPHIRA 320x256 2.5 microns cut-off 24 microns pixel pitch HgCdTe e-APD array allowing to obtain sub-electron readout noise, taking advantage of the APD noise-free multiplication gain and non-destructive readout ability. Another major AO wavefront sensing detector development concerns the RAPID project, also described here.

As an illustration of AO wavefront sensing capabilities, we have studied the interest of using such a low noise device for the Keck AO system.

## 2. THE RAPID E-APD INFRARED WAVEFRONT SENSING DETECTOR

### 2.1 Presentation of the RAPID research program

Developed by the SOFRADIR and CEA/LETI manufacturers, the RAPID infrared detector offers a 320x255 8 outputs 30 microns e-APD array, sensitive from 0.4 to 3 microns, with less than 2 e readout noise at 1600 fps. Advanced packaging with miniature cryostat using pulse tube cryocoolers was developed in the frame of this program in order to allow use on this detector in any type of environment. In 2013, the partners delivered the first prototypes and, given the performance results of these prototypes, the decision was quickly taken to push for an on-sky demonstration on a demanding instrument. PIONIER was chosen as its interferometric combination of light requires a very fast detector to fight against atmospheric turbulence, and a minimum amount of noise in order to detect faint objects. The RAPID detector is now implemented on the PIONIER instrument on the ESO/VLTI interferometer in Paranal since December 2014. Since this time, RAPID observed more than 150 stars during more than 45 nights on the VLTI with a tremendous gain compared to the previous camera based on conventional IR detectors.

### 2.2 The RAPID 320x255 pixel e-APD array presentation

The RAPID program was a 4 years R&D project funded by the French "Fonds Unique Interministériel" in 2009. It includes several industrial and academic partners from the field of advanced infrared focal plane arrays fabrication (SOFRADIR, CEA-LETI) and of astronomical/defense institutes (IPAG, LAM, ONERA). The goal of this program is to develop a fast and low noise infrared focal plane array of moderate format for astronomical fast applications. This research program is ongoing with FOCUS funding but the devices are currently not commercially available.

The main characteristics of RAPID are:

- Pixels Format: 320 x 255 pixels 30µm pitch
- Technology: HgCdTe, intra-pixel CDS and CTIA, sensitive from the visible to 3- 3.3 µm @ 77K
- Rectangular window can be defined with the start line and the end line of the window to be read.
- Noise: 1.6 e- with gain x14
- Frame rate: 1500 Hz, up to 2000 Hz
- Dark signal: 100 e-/s measured, limited by setup background
- Power consumption: 122 mW

The goal of the RAPID development was to demonstrate operation of the 320x255 pixels 30 microns pitch infrared array at 2000 fps with less than 2 e- readout noise. To achieve such readout noise and fast frame rate, APDs technology and intra-pixel Correlated Double Sampling were both needed. The floor plan of the device is shown in the Fig. 1, it includes

8 parallel outputs clocked at 20 MHz pixel rate defining 8 stripes of 40x256 pixels with one amplifier per stripe. The detector can be seen in the Fig. 2 during its integration in the pulse tube cryostat.

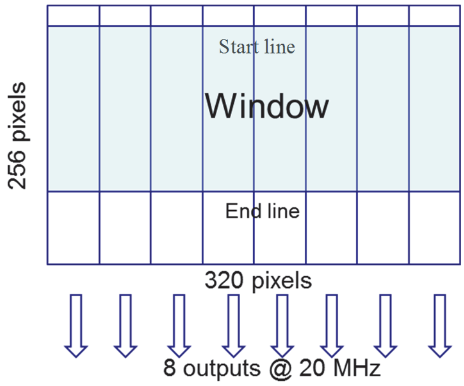


Fig. 1: The 1.6 kfps RAPID e-APD infrared detector configuration: 8 outputs 320 x 255 pixels with 30 µm pitch. A rectangular window with programmable start line and end line can be defined to speed up the frame rate.

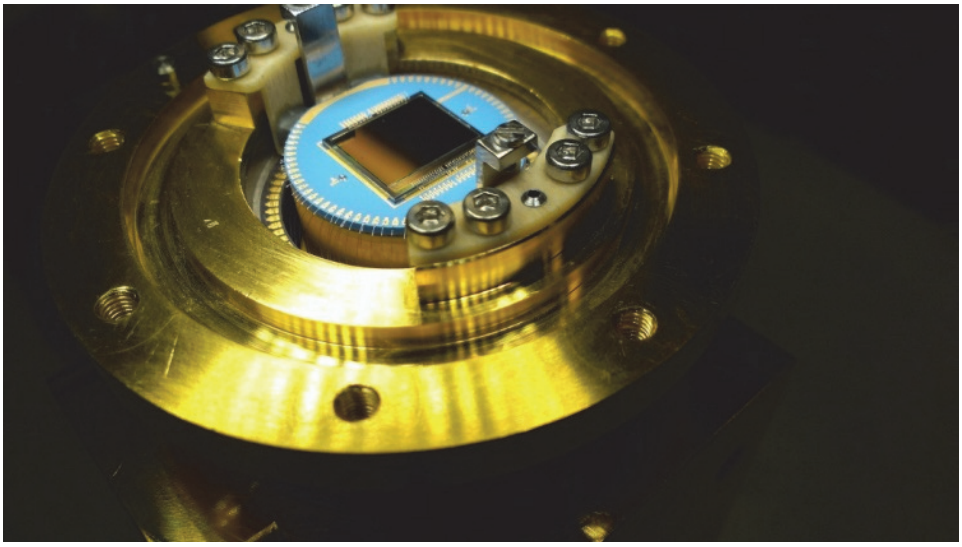

Fig. 2: The RAPID 320x255 IR APD array during integration by Sofradir in its cryostat cooled with a miniature pulse tube developed by the RAPID program.

### 2.3 RAPID detector results

The best performances compromise for RAPID was to use 3.3 µm cutoff photodiodes providing multiplication gain exceeding 25 and providing readout noise below 2 e. The current readout circuit of the detector limits the photodiode reverse bias voltage to 8V.

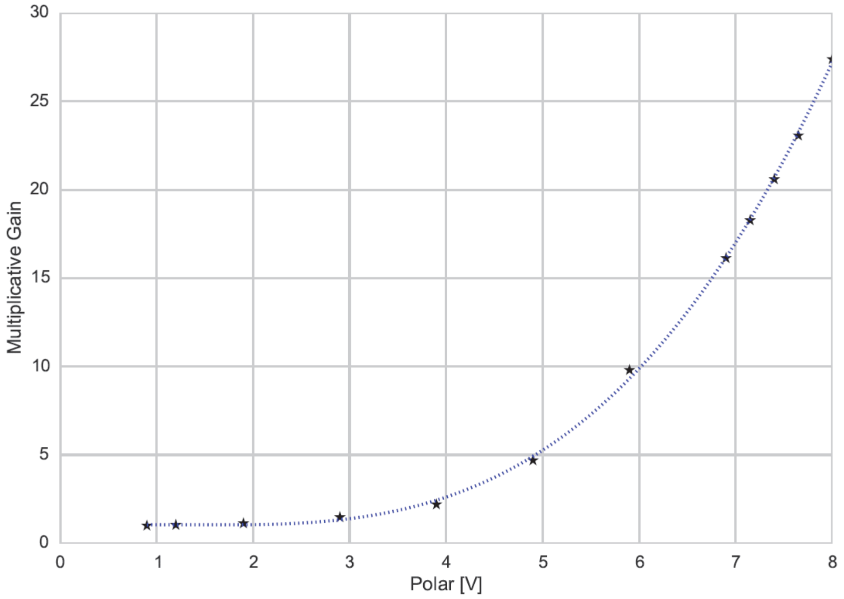


Fig. 3: Mean multiplication gain of the APD array as a function of the photodiode polarization voltage for 3.3 µm photodiodes cut-off.

Fig. 3 shows the multiplication gain as function of the photodiode voltage for the RAPID 3.3 µm cut-off array. As the cut-off wavelength is large, this allows to obtain high multiplication gain for a modest photodiode polarization. Sub-e readout noise for the maximum photodiode polarization can then be measured as it can be seen in the Fig. 4.

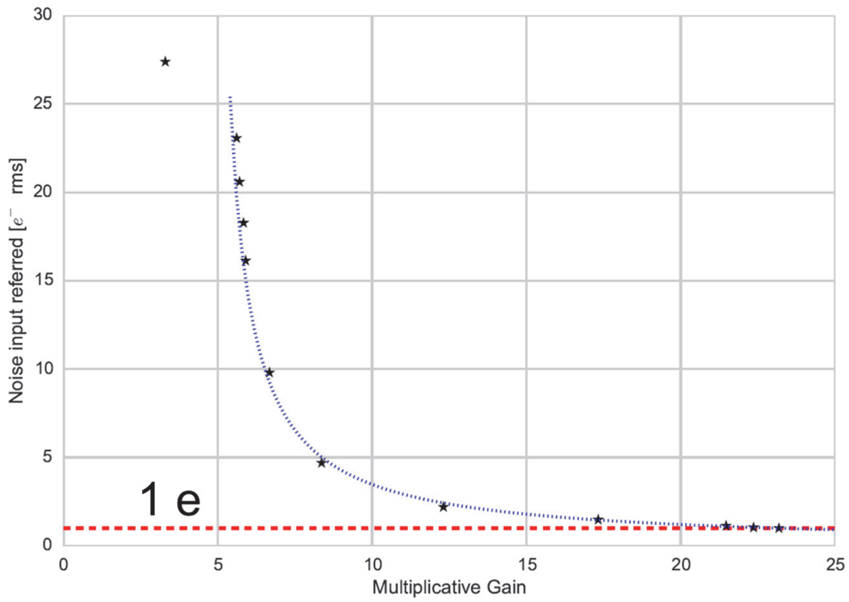


Fig. 4: Mean readout noise as a function of the multiplication for RAPID array with 3.3 µm cut-off.

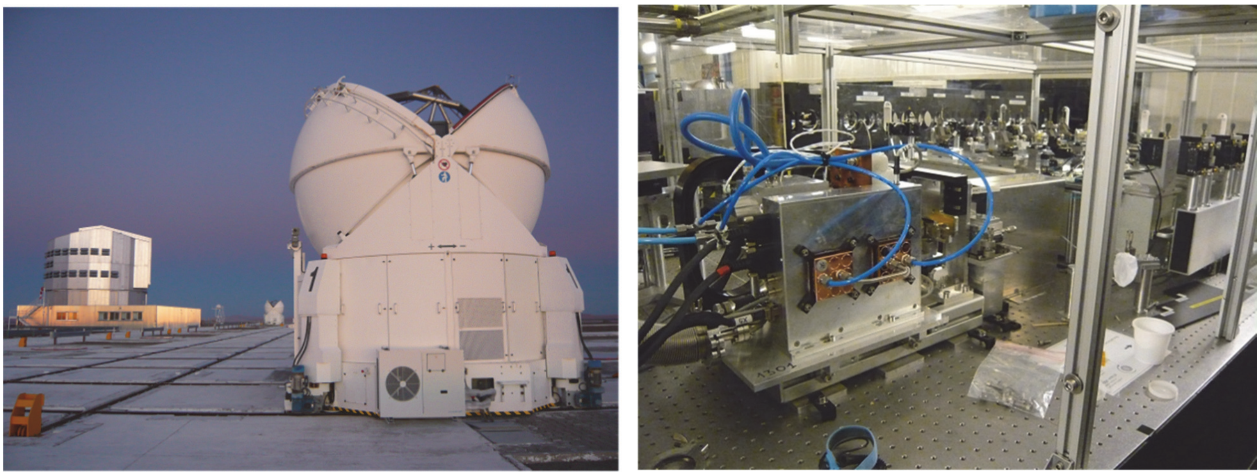

Fig. 5: The RAPID APD array installed on the ESO VLTI PIONIER instrument.

Fig. 5 shows the RAPID camera integrated on the PIONIER instrument [8] in December 2014. The PIONIER instrument combines the light from the 4 VLTI Auxiliary Telescopes on Paranal. The RAPID camera is producing scientific observation for this instrument since this date. The Fig. 6 shows the RAPID readout noise histogram with a multiplication gain of 25, demonstrating that a median readout noise of 0.75 e noise at 1600 fps was routinely measured while the camera was operated on the telescope.

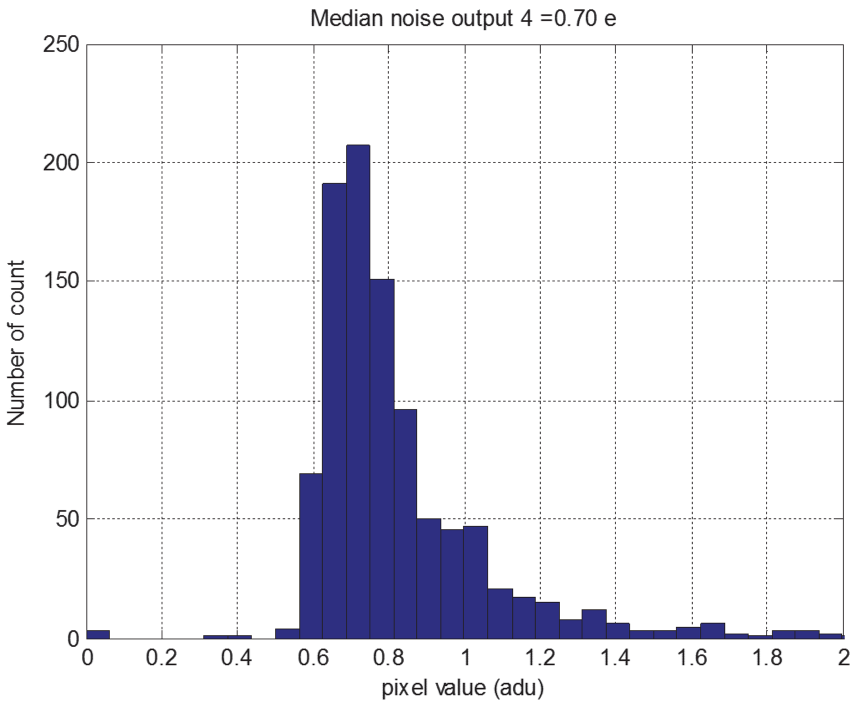


Fig. 6: The RAPID noise histogram as measured in Paranal (ESO, Chile) on the PIONIER ESO/VLTI instrument. The median noise measured here is 0.7 e for a multiplication gain of x25. The detector temperature is 75 K and the frame rate is 1600 fps.

## 3. THE C-RED ONE INFRARED APD CAMERA FROM FIRST LIGHT IMAGING

### 3.1 The C-RED one infrared APD camera presentation

C-RED is a unique commercial infrared camera using the Selex Saphira 320×256 pixels HgCdTe e-APD array with 24 microns pixel pitch. C-RED is developed by First Light Imaging [4]. The sensor cutoff wavelength is 2.5 microns and it allows sub-electron readout noise, taking advantage of the e-APD noise-free multiplication gain and non-destructive readout ability. C-RED is also capable of multiple regions of interest (ROI) readout allowing faster image rate (10s of kHz) while maintaining unprecedented sub-electron readout noise.

The sensor is placed in a sealed vacuum environment and cooled down to cryogenic temperature (70K) using an integrated pulse tube, with a high reliability (MTBF > 90,000 h) much higher than standard Stirling coolers used usually with cooled infrared arrays.

The Fig. 7 shows a picture of the C-RED one camera prototype. The commercial camera will include a special housing, not shown in this figure, to protect the fragile components of the system and to avoid water condensation inside the camera. On top of the camera, the helium compressor for cooling the pulse tube can be seen on this figure.

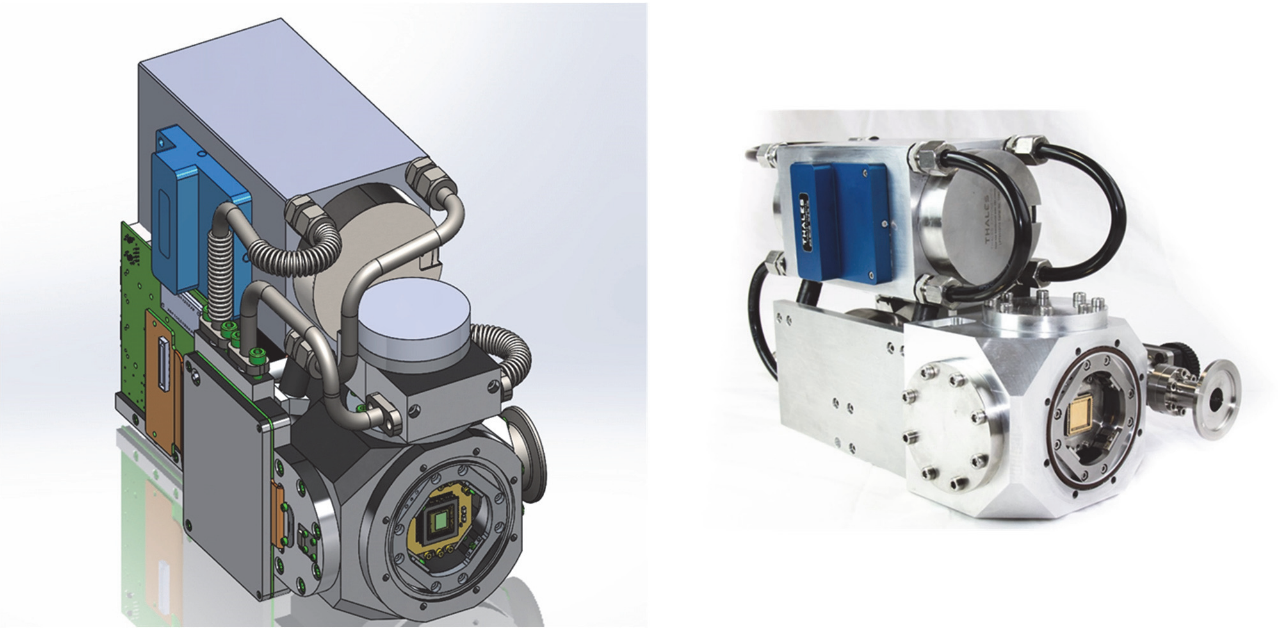

Fig. 7: The C-RED one infrared camera commercialized by First Light Imaging and that uses the Selex Saphira infrared array.

### 3.2 The Selex Saphira detector of C-RED one.

Designed and fabricated by Selex, the Saphira detector is designed for high speed infrared applications and is the result of a development program alongside the European Southern Observatory on sensors for astronomical instruments. It delivers world leading photon sensitivity of <1 photon rms with Fowler sampling and high speed non-destructive readout (>10K frame/s). Saphira is an HgCdTe avalanche photodiode (APD) array incorporating a full custom ROIC for applications in the 1 to 2.5µm range.

Like the RAPID detector, SAPHIRA uses the HgCdTe APD properties, offering sub-electron noise with multiplication gain up to x80. The pixel format is 320x256 pixels with 15fF integration node capacitance (30fF with HgCdTe diode). The array has 32 parallel video outputs, organized as 32 sequential pixels in a row. The 32 outputs are arranged in such a way that the full multiplex advantage is available also for small sub-windows. Non-destructive readout schemes with subpixel sampling are possible. This reduces the readout noise at high APD gain well below the sub-electron level at frame rates of

1 KHz. The growth technology used now is the metal organic vapor phase epitaxy (MOVPE). This growth technology provides more flexibility for the design of diode structures. It is possible to make heterojunctions with different bandgap properties between the absorption region and the multiplication region. The change to MOVPE resulted in a dramatic improvement in the cosmetic quality with 99.97 % operable pixels at an operating temperature of 85K. The avalanche gain is controlled by an external voltage. The digital and analog functions are controlled by a serial interface. The readout of Saphira allows to read multiple windows, each independently resettable. Glow protection and APD protection circuit are also included.

Fig. 8 shows the functional bloc diagram of the ME911 SAPHIRA readout circuit used currently in C-RED. In 2016, C-RED one will switch to the ME1000 version of the Saphira readout circuit. The ME1000 scanning modes include a Read-Reset-Read per row function, so the user can have complete control of the correlated-double-sampling process. Saphira ME1000 also incorporates glow suppression by using 100% metal screening. A reset current limit function has been added in this readout circuit version to protect the array from short circuit APDs.

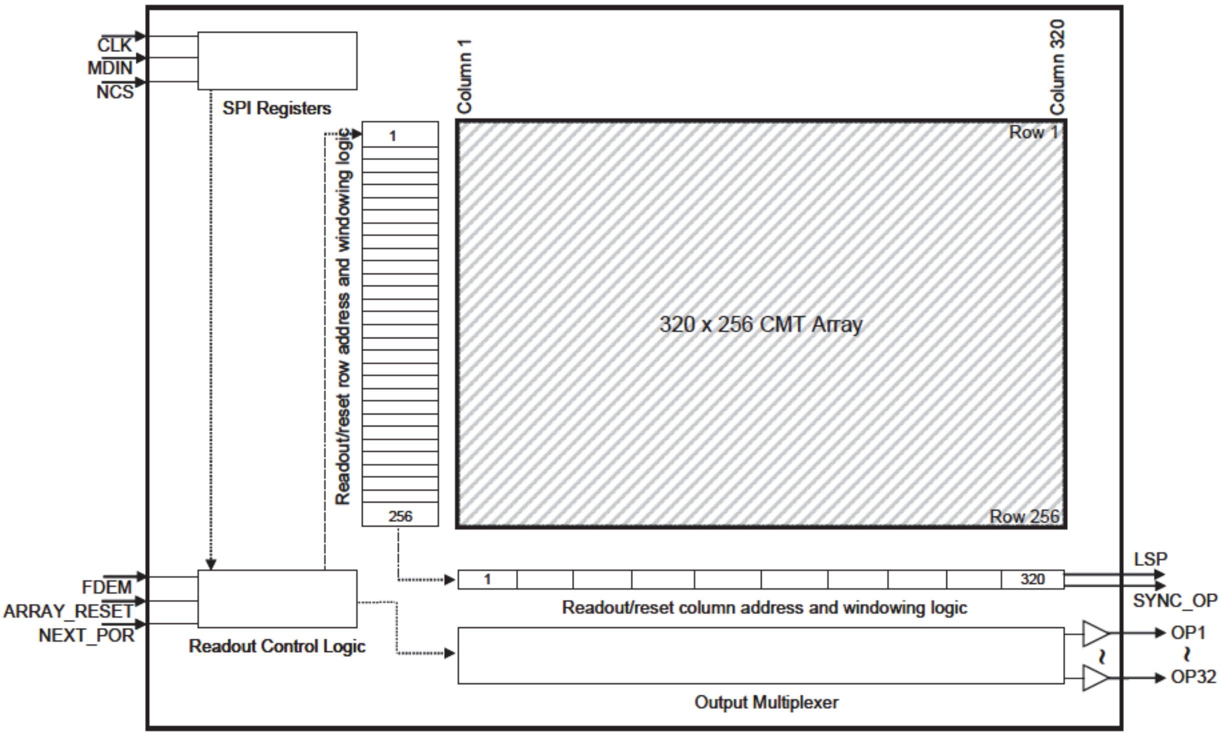


Fig. 8: the SELEX SAPHIRA ME 911 readout circuit architecture.

### 3.3 The C-RED camera characteristics and performances

The C-RED one camera has the following main characteristics:

- MCT near IR Avalanche Photo Diode 320x256 with Selex Saphira detector.
- Sub-electron readout noise.
- 32 outputs, up to 3500 fps.
- Mean Readout noise at 2000 fps and gain 60 of <1 e.

- 70% QE.
- Zynq System on Chip from Xilinx embedded.
- Supported readout modes: read-reset-read per row, embedded multiple non-destructive readout, rolling reset.
- Pulse tube packaging cooling down to 50 K.
- Custom design available: custom beam aperture and cold pupil, custom cold filter and custom cold optics are possible.
- Cameralink full interface.

In addition, the Table 1 below shows the predicted performance of the camera:

| Test | Result |
|---|---|
| Mean Dark + RON | <1 e- |
| Digitization | 16 bits |
| Operating Temperature | 80 K |
| Mean Quantum Efficiency from 1.3 to 2.5 µm | 70 % |
| Operability +/-30 % | 99.3 % |
| Image full well capacity | 200 000 e- |
| Excess noise factor F | 1.25 |

Table 1: Predicted performances of the C-RED one camera

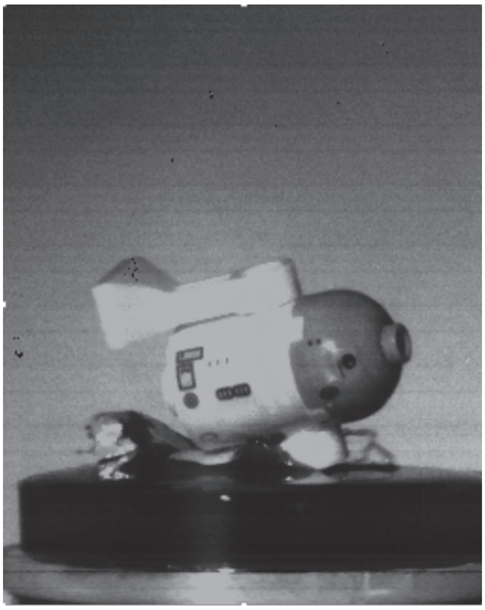

Fig. 9: C-RED one world record movie at 3500 fps, the detector is operated at 85K in a rolling reset readout mode.

Fig. 9 shows a movie of C-RED one in Rolling Reset readout mode with a frame rate of 3500 fps full frame, which is apparently a world record for infrared full frame imaging.

### 3.4 Signal to noise comparison between detector technologies

At various illumination levels, the Signal to Noise-Ratio (SNR) of various visible and infrared detectors is computed as:

$$SNR = \frac{QE * S}{\sqrt{QE * S * F + \left(\frac{\sigma}{G}\right)^2}}$$

In this equation, the detector is assumed to be fast enough to have negligible dark signal. Here, S is the illumination signal (in photons/pixel/image), QE is the detector quantum efficiency, σ is the readout noise, G the multiplication gain and F is the excess noise factor. A comparison of infrared detectors shows how much an e-APD sensor can improve the SNR for faint fluxes and also that its sensitivity in the infrared is directly comparable to EMCCDs in the visible—the latter of which are considered to be the most sensitive detectors (see Fig. 10).

Currently, the gain in performance of EMCCDs compared to classical CCDs in the visible is smaller than the gap between C-RED One and its competitors— whether they be slow-scan HgCdTe or even indium-gallium-arsenide (InGaAs)-based cameras. This advance in performance characteristics should allow e-APD imagers to usher in a new era in high-performance infrared detection.

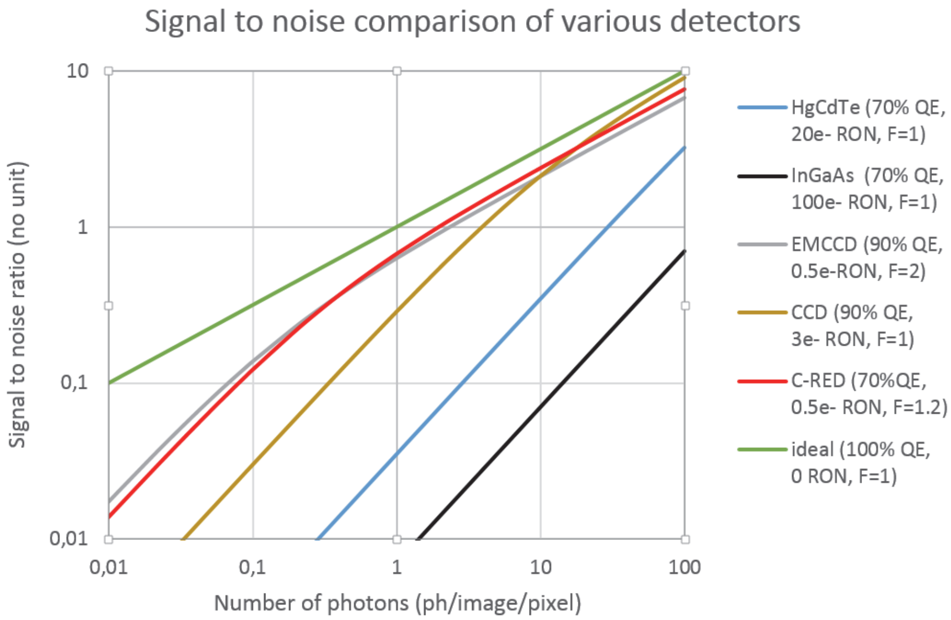


Fig. 10: Signal to Noise comparison of various detector technologies. CCD and EMCCD are sensitive in the visible. They are compared with IR detectors (InGaAs, slow scan HgCdTe and the C-RED e-APD camera).

### 3.5 Infrared wavefront sensing at Keck: interest of the infrared APD technology versus classical infrared arrays

A near-infrared (NIR) tip-tilt sensor based on multiple reads of a small region (e.g. 4x4 pixels) of an H2RG-based camera has been implemented with the Keck I laser guide star (LGS) adaptive optics (AO) system [9]. The performance results are good which has prompted Keck to propose for a similar sensor for the Keck II LGS AO system. An analysis was performed to evaluate the options given the recent developments in NIR APD arrays. The options are to largely reproduce the Keck I system or to implement a new system based on a NIR APD array.

For the APDs the amplified signal, QE.G.S, is the multiplication of the multiplication gain G for an amplified detector, the quantum efficiency of the detector, QE, and the number of guide star photons per sub-aperture, S. The amplified noise,

$[FG^2(QE*S + nN_B + nN_D) + nN_R^2]^{1/2}$ depends on the signal, the excess noise factor, F, relevant for an amplified detector, the gain, the number of pixels, n, and the background noise, $N_B$, dark noise, $N_D$, and read noise, $N_R$, per pixel. The impact of the multiplication gain is to reduce the effective read-noise.

A plot of SNR versus magnitude is shown in Fig. 11. The APD outperforms the H2RG for the 4x4 pixel case except for ≥ 15 magnitude; this will move to fainter magnitudes as the thermal background (i.e. due to the throughput and temperature of the AO bench optics) decreases. The higher SNR performance for the APD system allows an APD system to be operated at higher bandwidth than an H2RG system while maintaining the H2RG SNR level. The APD's performance advantage over the H2RG increases with the number of pixels (e.g. the APD's can be used for a high order wavefront sensor). There is little performance difference between the two detectors in the 2x2 pixel case as shown in the right plot in Fig. 11.

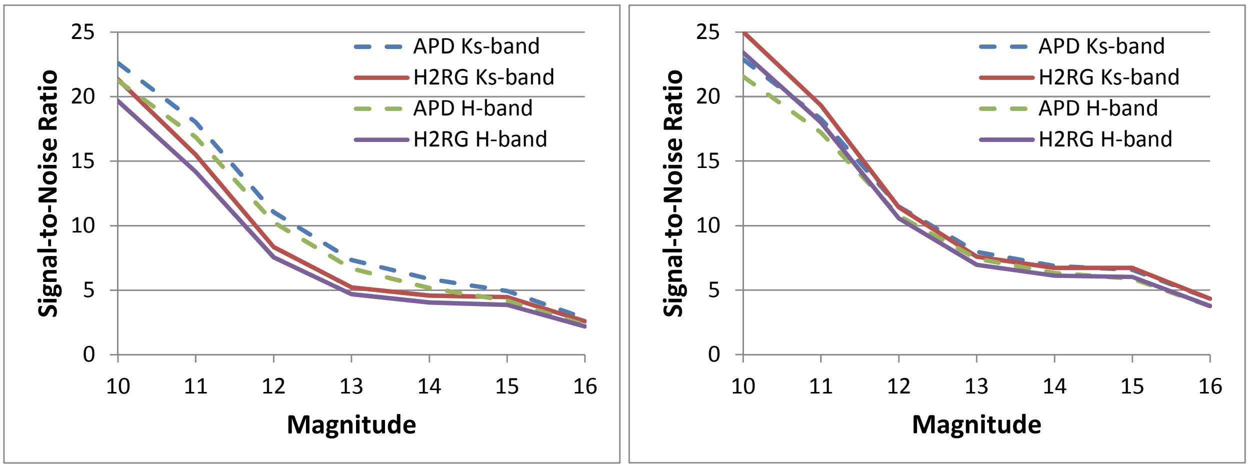


Fig. 11: SNR versus magnitude (4x4 pixels left and 2x2 pixels right). Assumptions: 4x4 pixels, 0.05 arcsec/pixel, 49% throughput & 20% K-band Strehl ratio; frame rates of 800, 500, 500, 400, 200, 75, 50 Hz for 10 to 16th magnitude respectively. Q = 70% for Selex and 85% for H2RG with an additional 89% throughput term because of additional optics.

## 4. CONCLUSION

This paper illustrates a long term and coordinated wavefront sensor development in Europe involving cutting edge detectors and camera systems industry associated with ESO, academic French laboratories (LAM, IPAG and OHP) and First Light Imaging. Among these developments, a huge effort has been made on e-APD infrared arrays, together with the parallel development of state of the art camera systems using this disruptive technology.

One of these IR devices is called RAPID and is based on a 1.6 kfps 320x255 pixels infrared APD array. This detector is now permanently installed on the ESO VLTI telescopes as focal plane camera for the PIONIER instrument. This is the first time a visible-infrared APD fast detector (1700 fps, 1 e- noise) is producing permanent astronomical data on a large world class telescope.

In the meantime, the C-RED ONE infrared camera is currently developed by First Light Imaging, taking advantage of the 320x256 Selex SAPHIRA e-APD characteristics and performances in its latest and most advanced version. A frame rate world record for an infrared camera of 3500 FPS has been achieved. The C-RED one development program is continuing and the prototype camera is currently under characterization tests.

## 5. ACKNOWLEDGMENTS


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## REFERENCES

[1] P. Feautrier et al., "Advances in detector technologies for visible and infrared wavefront sensing", Proc. SPIE, 8447, 84470Q (Sept. 13,2012).
[2] G. Finger et al., "SAPHIRA detector for infrared wavefront sensing", Proc. SPIE, 8453, 84530T (Sept. 25, 2012).
[3] P. Feautrier et al., "Revolutionary visible and infrared sensor detectors for the most advanced astronomical AO systems", Proceedings of the SPIE, Volume 9148, id. 914818 16 pp. (2014).
[4] First Light Imaging SAS, http://www.first-light.fr
[5] J. Rothman *et al.*, "HgCdTe APDs for space applications", ICSO 2014 - International Conference on Space Optics, 7 - 10 October 2014, Tenerife, Canary Islands, Spain.
[6] G. Finger, "SAPHIRA detector for infrared wavefront sensing", Proc. SPIE. 9148, Adaptive Optics Systems IV, 914817. (August 07, 2014) doi: 10.1117/12.2057078.
[7] S. Derelle et al., "A Monte Carlo study of multiplication and noise in HgCdTe avalanche photodiodes," Proc. SPIE 7003, 70031P (Apr. 2008).
[8] J. B. LeBouquin et al., "PIONIER: a 4-telescope visitor instrument at VLTI", 2011, A&A, vol. 535, article id 67.
[9] R. Rampy et al., "Near-infrared tip/tilt sensing at Keck: System architecture and on-sky performance", Proc. of AO4ELT4 (2015).