Developments in Infrared e-APD Wavefront Sensing Camera Technology

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Abstract

We present ongoing developments toward the realisation of an infrared wavefront sensing camera with sensitivity, speed, and size sufficient to enable adaptive-optics-assisted characterisation of Earth-like planets with extremely large telescopes. As part of the Cassiopée project and building on the success of the C-RED One from First Light Imaging, a wavefront sensing camera is under development that incorporates the latest 512 x 512 Saphira e-APD sensor array from Leonardo. We will describe innovations and techniques contributing to the improvement and maturation of this technology. These include integration of active vibration control in the camera's pulse tube cryocooler and sensor/camera design elements that improve suppression of both dark current and infrared background signal. In the context of these updates, we report both our predictions for the camera's final performance specifications and the status of the project.

The planet-hunting instruments of tomorrow, which aim to discover Earth-like planets in nearby star systems by 2035, must be capable of delivering image contrast of order 10^9. Rapid and high-resolution Adaptive Optics (AO) systems are critical to achieving this by ensuring that the coming generation of extremely large telescopes can meet their design specifications in terms of sensitivity and spatial resolution. The Cassiopée project brings together partners from industry (Oxford Instruments First Light Imaging and ALPAO) and academia (LAM and ONERA) to develop an AO system with the performance needed to meet these challenges. A detailed description of the system's AO loop has been reported by Neichel et al. [1]. This poster focuses on new technology developments related to the system's wavefront sensing camera (hereafter referred to as the Cassiopée camera) which is based upon the successful C-RED One camera developed by First Light Imaging alongside the European Southern Observatory (ESO; see Fig. 1) [2-4] . This poster presents the technology giving these cameras their signature sensitivity and speed (Figs 2 & 3) alongside developments leading to reductions in dark current (Fig 4), thermal background (Fig. 5), and residual camera vibration (Fig 6).

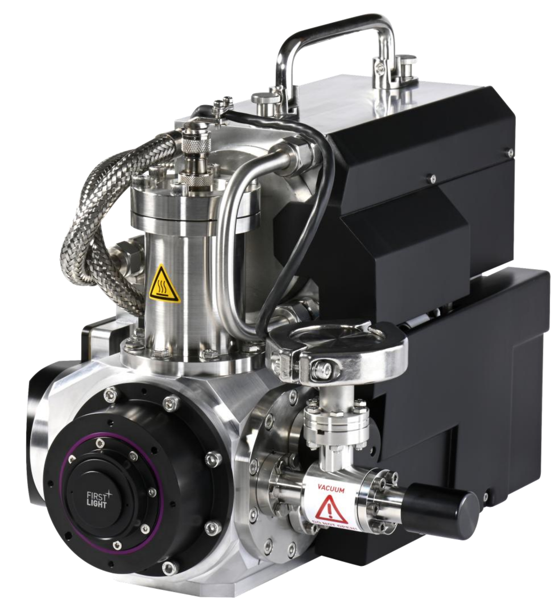

Figure 1 - C-RED One (right) is a high-speed electron-multiplied infrared camera fabricated and commercialised by Oxford Instruments First Light Imaging. It offers world-leading single photon sensitivity and rapid non-destructive readout at 1000s of frames/s. Details on C-RED One's Saphira sensor are outlined below. C-RED One is an autonomous user-friendly plug-and-play system that can be operated in remote locations. The sensor is enclosed in a self-managing vacuum chamber and is cooled to <90 K with an integrated cryogen-free pulse tube cooling system. The camera is described extensively by Feautrier et al. [5]. Learn more about C-RED One by scanning the QR code on the left.

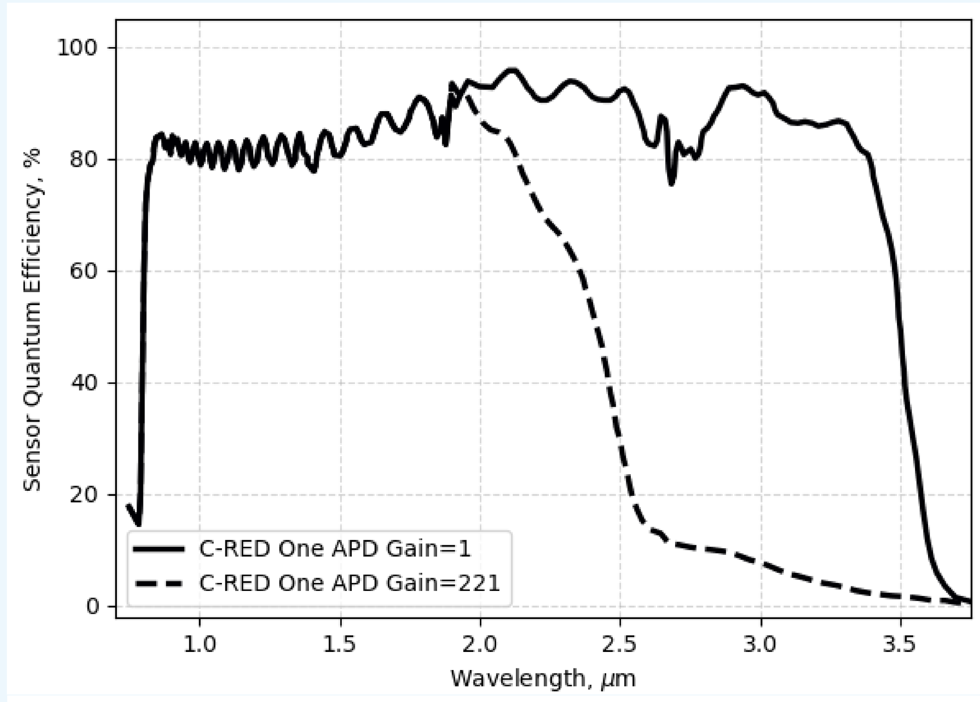

Figure 3 - Quantum Efficiency curve for Saphira e-APD sensors. Digitised from Finger et al. [6].

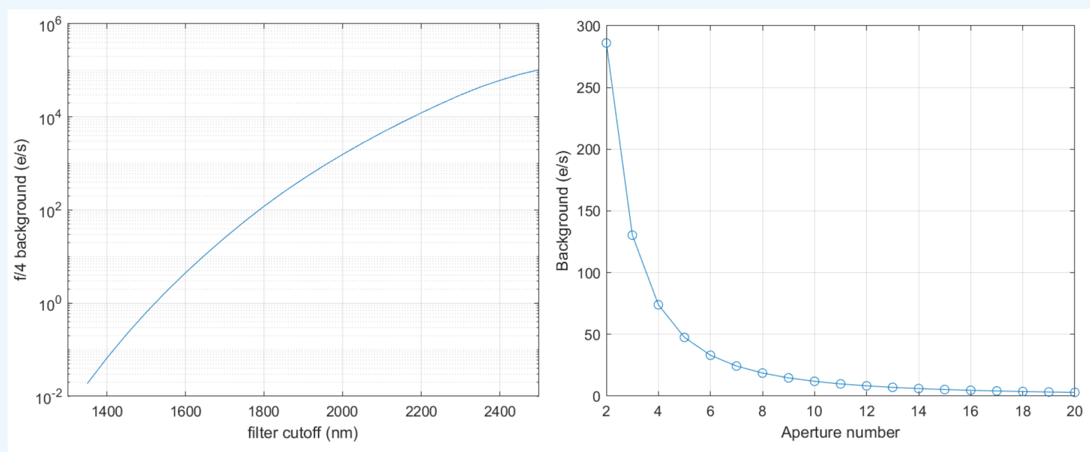

Figure 5 – Simulated per-pixel thermal background flux detected by C-RED One when viewing a scene at 293 K: (Left) effect of thermal filter cutoff wavelength for an f/4 input beam; (Right) effect of the input beam aperture with filter cutoff wavelength set to 1.75 μm. Real measurements are in accordance with these curves. The extremely low read noise and dark current noise in these cameras combined with the extension of their sensitivity into the thermal infrared results in high sensitivity to thermal background photons and their shot noise. Care must be taken to block this background with filters and/or baffles. Cooling the camera's fore-optics will also reduce detection of unwanted thermal background photons. All these options are possible with C-RED One, with most users choosing the cold filter approach to transmit in J & H bands and block thermal photons in K & L.

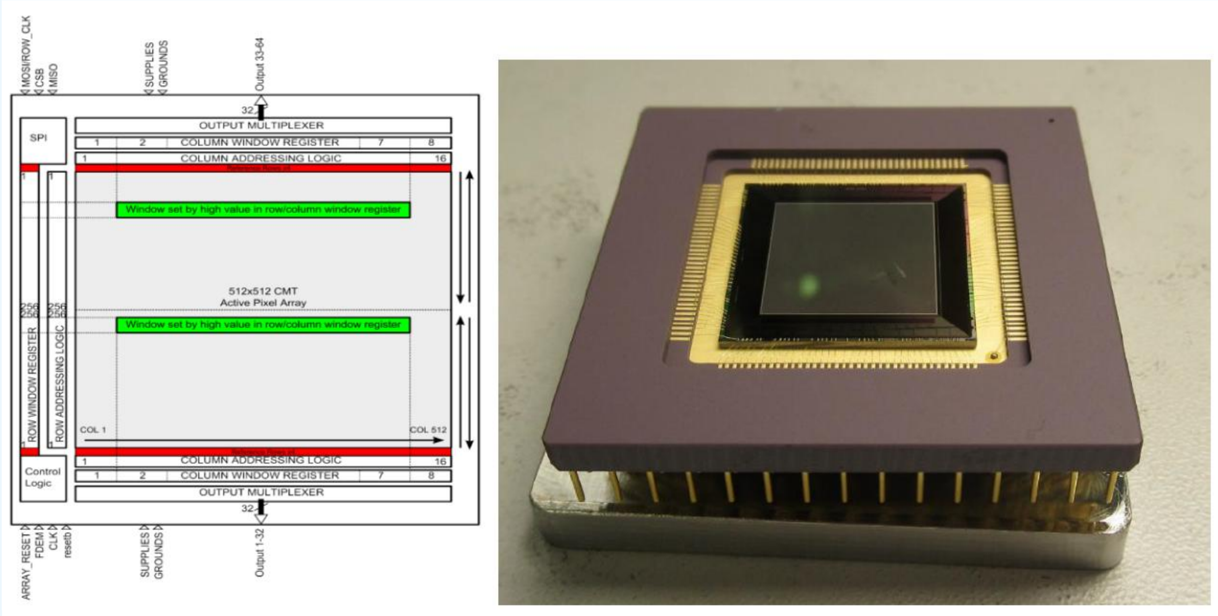

Figure 2 - At the hearts of both C-RED One and the Cassiopée camera are Saphira HgCdTe Linear mode Avalanche Photodiode (Lm-APDs) arrays manufactured by Leonardo UK (pictured). These sensors are also known as electron initiated APDs (e-APDS). As APD arrays they support application of avalanche gain that allows signal to be multiplied above the read noise, even if rapid high-bandwidth readout is used. This, in turn, allows these sensors to image at kHz rates without loss of relative sensitivity. C-RED One integrates a 320x256 pixel array, while the Cassiopée camera will integrate the larger 512x512 ME1130 variant (Full camera specs in Table 1). A bloc diagram and photograph of the ME1120 ROIC is shown above. The quantum efficiency (QE) of both sensors (measured by Finger et al. [6]) is plotted in Fig. 3.

Parameter	Value
Format	512 x 512
Pixel Pitch	24 μm
Shuttering	Global
Full Well	>20 ke-
Single Read Frame Rate	3000 FPS (2300 FPS minimum)
Correlated Double Sampling Frame Rate	1500 FPS
Read Noise @ 3000 FPS and gain ~50 observing 80 K black body	<1 e-
Total background (dark + thermal) @ 3000 FPS and gain ~10 observing 80 K black body in a room temperature scene with f/4 beam and 1.7 μm filter cutoff	<30 e-/pixel/s
Dark current at gain ~10 observing 80 K black body	<5 e-/pixel/s
Quantization	14 or 16 bit
Detector operating temperature	80 K
QE at 1.1-2.4 μm	>70%
Excess noise factor	<1.25
Residual pulse tube vibration at detector	<1 μm RMS
Filtering	Fixed thermal background cold filters with cutoff at 1.7 μm
Data interface	Two 10 GigE ports or two CoaXPress 12 ports.

Table 1 – Expected Cassiopée camera performance.

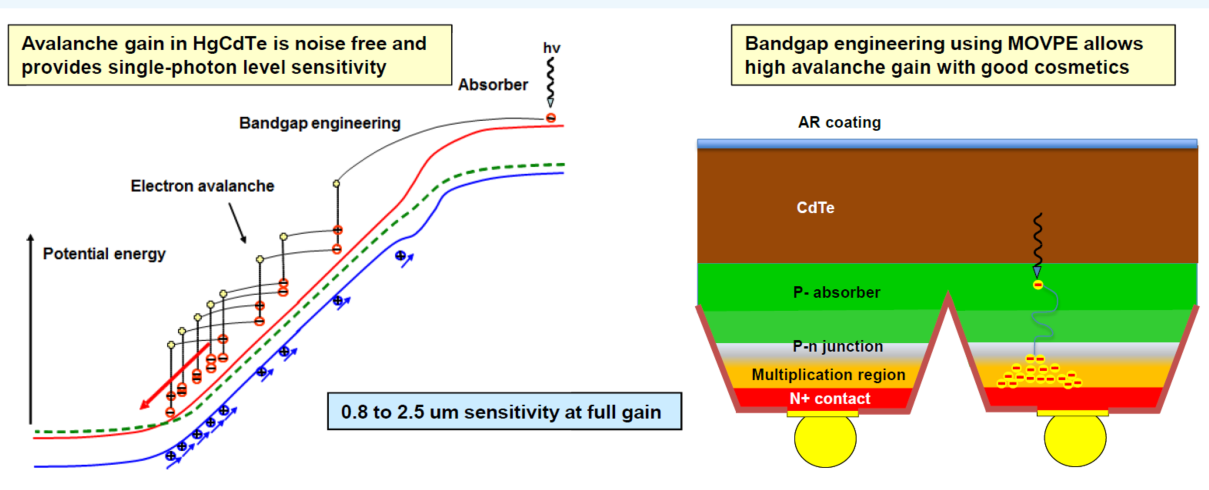

Figure 4 – Metal Organic Vapour Phase Epitaxy (MOVPE) design and device schematic for a HgCdTe e-APD sensor (courtesy of Leonardo). Growth of these sensors by MOVPE on a slightly mismatched (100) GaAs substrate allows for the engineering of a more complex band gap and doping profiles that greatly reduce junction-related sources of dark current. Bandgap engineering also allows selective amplification of photoelectrons without amplification of thermal electrons. As a result, the MOVPE grown mesa diodes in Saphira sensors are intrinsically less sensitive to dark current than similar sensors grown via other methods (e.g. Liquid Phase Epitaxy).

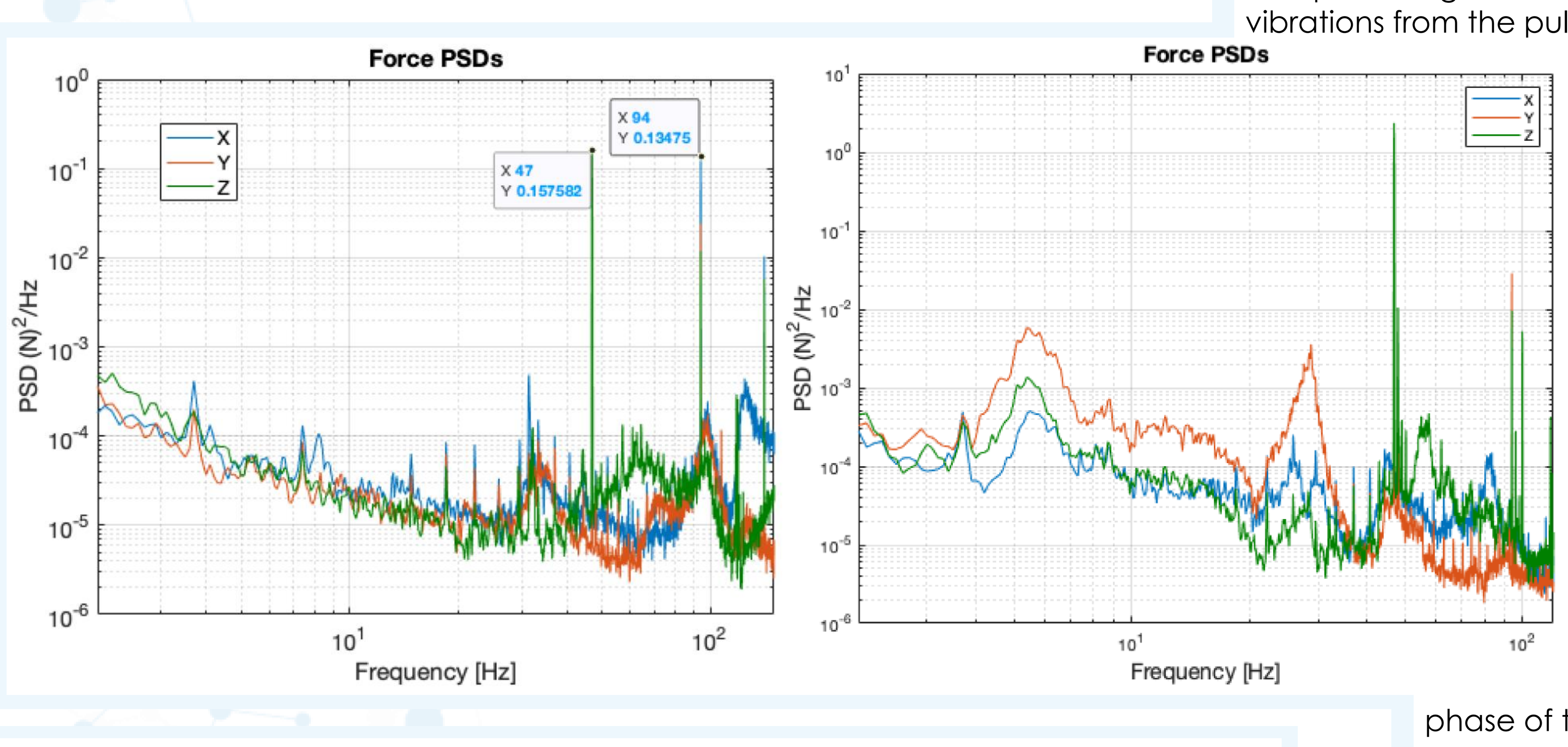

Figure 6 – Force spectrum of camera induced vibrations with (left) and without (right) active vibration control. Note the different log scale between the two plots (measurements courtesy of ESO). C-RED One's pulse tube cooler thermoacoustically chills the camera's sensor to <90 K without need for cryogens like liquid Helium or LN2. The linear motions of the pistons (voice coils) in the tube have opposing phase and therefore a compensating momentum. This means that forced vibrations from the pulse tube are already small, with residuals resulting mainly from either imperfect match in mass between the pistons or voice coil driving phase error. To minimise these residuals First Light Imaging worked with ESO to develop a Vibration Control System (VCS) that attaches a MEMS accelerometer to the cooler's compressor with sensitivity in the piston displacement direction. The accelerometer's readout is used to adjust the individual driving phase of the voice coils and compensate for residual mismatches in compressor construction. This system was first successfully implemented on the C-RED One for the E-ELT Phasing and Diagnostic Station. It is now offered as an optional extra for all C-RED One cameras.

References: **[1]** Neichel et al. 2024, Proc. SPIE Adaptive Optics Systems IX, 130971G; **[2]** Gach & Feautrier 2015, Laser Focus World, *https://www.laserfocusworld.com/print/content/16551550*; **[3]** Finger et al. 2012, Proc. SPIE 84530T; **[4]** Feautrier et al. 2015, "State of the art IR cameras for wavefront sensing using e-APD MCT arrays", AO4ELT4; **[5]** Feautrier et al. 2017, Proc. SPIE 102090G; **[6]** Finger et al. 2023, Astron. Nachr. 344, e20230069

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