# The C-RED fast infrared camera family for wavefront sensing

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**Abstract.**
We present here the latest results obtained with the CRED One camera. This camera uses the Leonardo (previously Selex) Saphira e-APD 320x256 infrared sensor in an autonomous cryogenic environment using a low vibration pulse tube and with embedded readout system. We will present tradeoffs with using the camera in a real environment. Whereas many authors give the raw sensor performance, we will account for background issues, filtering and thermal photons rejection all the noise sources of the camera. Commercially available, sub-e noise is routinely achieved with this system at frame rates as high as 3500 fps. Also commercially available, we present in addition the C-RED 2 camera, based on a fast and low noise InGaAs sensor and see the advantages of such a technology for medium-end wavefront sensing applications (tip-tilt correction and low order infrared wavefront sensing). Sensitive from 0.9 to 1.6 microns, the camera provides 600 FPS 640x512 full frame images with total noise of 30 e. The both cameras are designed to be easily operated on a telescope with demanding environment. Liquid nitrogen and vacuum pump free, they do not need complex cryogenic operation without any compromise on the detector performances.

**Keywords:** infrared, e-APD, InGaAs, fast imaging, low noise, wavefront sensing, interferometry

## 1 INTRODUCTION

### 1.1 The Saphira Detector and C-RED One camera

C-RED1 is an ultra-low noise infrared camera based on the Saphira detector and fabricated by First Light Imaging, specialized in fast imaging camera, after the successful commercialization of the OCAM2 camera [1] dedicated to extreme adaptive optics wavefront sensing. Designed and fabricated by Leonardo UK, formerly 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 [2], [3], [4]. 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. C-RED One camera is an autonomous plug-and-play system with a user-friendly interface, which can be operated in extreme and remote locations. The sensor is placed in a sealed vacuum environment and cooled down to cryogenic temperature using an integrated pulse tube. The vacuum is self-managed by the camera and no human intervention is required. The system shown in Figure 1 has been extensively described by Feautrier et al. in 2017 [5].

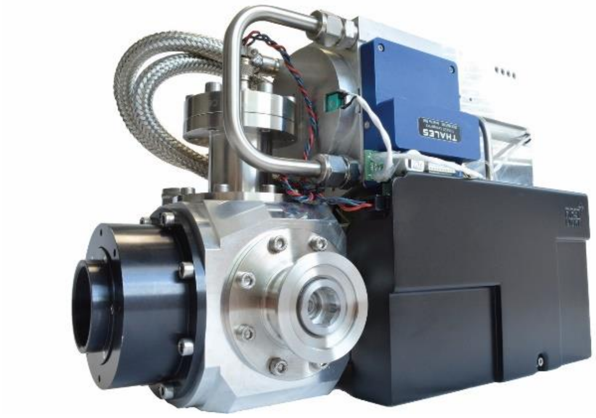


*Figure 1: the C-RED One camera. The cooling system (pulse tube) can be seen on the top whereas in the bottom are the vacuum cryostat and the readout electronics.*

# 2 C-RED ONE PERFORMANCES

The measurements were all made at 80K operating temperature, using a MARK 13 engineering grade SAPHIRA device. This device is supposed working as a science grade except for cosmetics which should be degraded.

## 2.1 Quantum efficiency

The array quantum efficiency peaks up to near 80% and the array AR coating may be optimized for J, H or K bands (H band is the standard one). Figure 2 shows the effect of this QE optimization. Moreover, due to junction heterostructure with 3.5 µm cutoff wavelength HgCdTe material for the avalanche multiplication region and 2.5 µm material for the absorber, the device is sensitive in L band at gain 1 but not with APD gain. This is due to photon penetration depth (longer wavelength photons penetrate deeper in the material and therefore are less amplified). We've measured that already with low gains (in the range of 5 to 10) the L band sensitivity is decreased to near zero, leaving only J, H and K sensitivity.

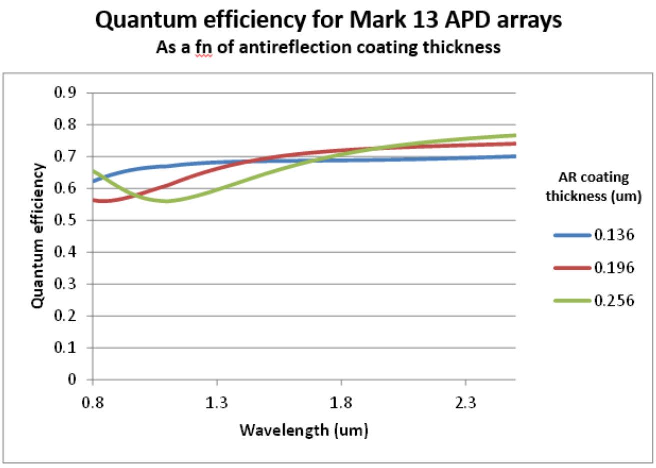


*Figure 2: AR coating and QE optimization for J, H or K bands of Mark13 e-APD diodes. The H band coating is the standard one.*

## 2.2 Conversion gain

The system gain is measured illuminating the sensor in CDS mode with a flat field through an integrating sphere with the well known Photon Transfer Curve method. The mean variance is plotted as function of the mean signal, the inverse slope of the linear regression gives the conversion gain of the camera in e/ADU.

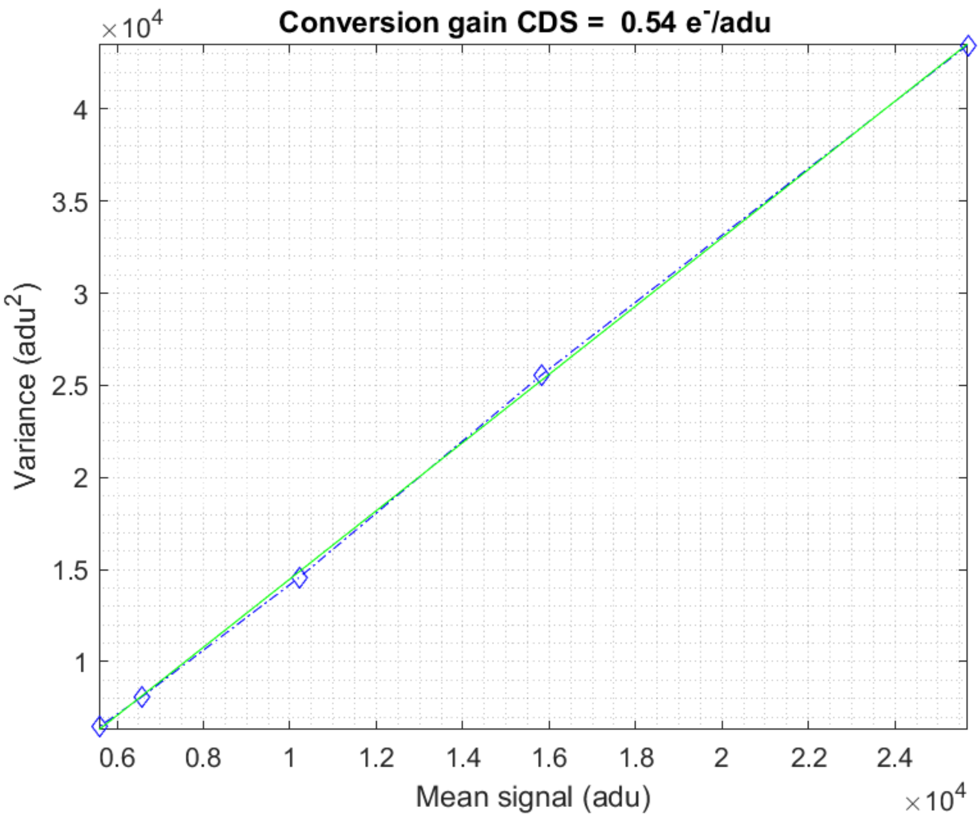


*Figure 3: Photon transfer curve of single readout mode (left) and CDS mode (right).*

## 2.3 APD gain

APD gain is measured by illuminating the sensor with a weak IR laser light at 1300nm. APD gain is then applied, and the ratio of ADU change over reference level gives the gain.

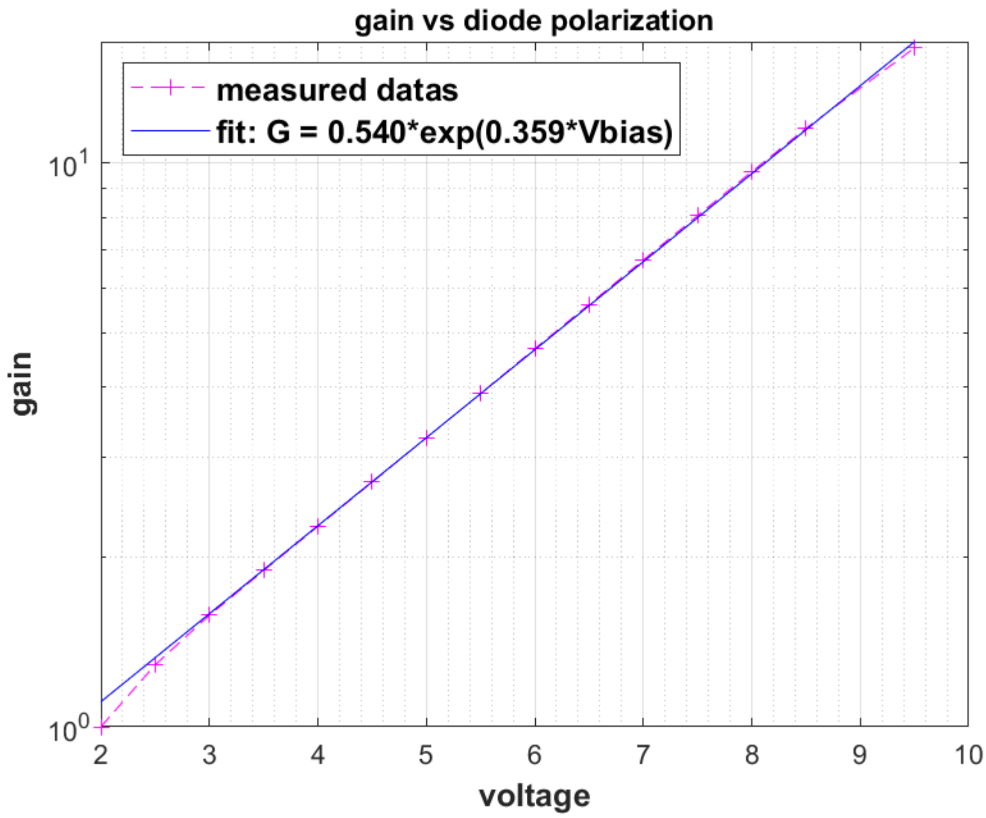


*Figure 4: Measured APD gain vs polarization voltage of C-RED One and exponential fit.*

### 2.4 System noise

The noise measurement is done by measuring the temporal variation of the image, sensor in the dark running at 1700fps.

Figure 5 shows the total system readout noise in CDS (Correlated Double Sampling) readout mode at multiplication gain x50 and 1720 FPS readout. Total system noise as low as 0.18 e is measured at gain 50 and 1720 fps in CDS readout mode.

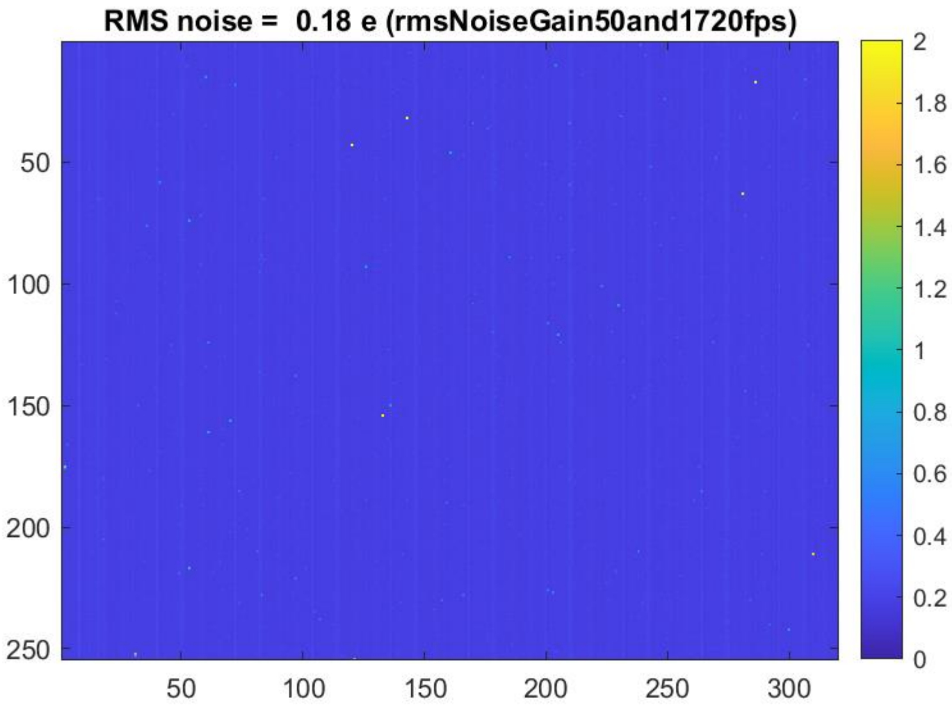


*Figure 5: Measured input referred readout noise vs APD gain for single readout and CDS readout.*

### 2.5 Dark current

To do this measurement the sensor is in the dark, looking at a 80K cold stop. The dark current is measured by fitting a line over the ADU level vs exposure time graph. The slope of this line gives the mean dark count. Very low dark current in the order of 3 e/s are now measured in our system.

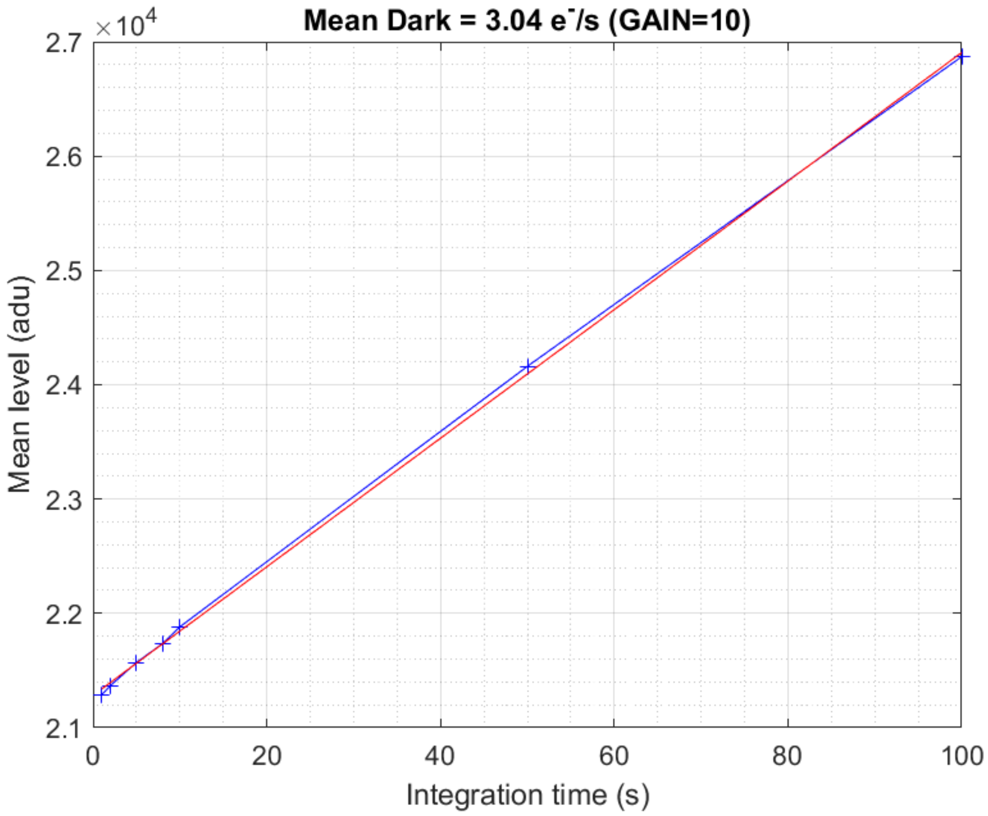


*Figure 6: Measured dark current vs gain at different speed (right scale in MHz) and readout modes*

### 2.6 Background measurement

The background current is measured the same way it is for the dark current but looking at a room temperature blackbody. This is in fact representative of what the user will have in real camera operation.

The Figure 7 shows the camera background when looking at a room temperature (305K) blackbody with the detector at 80K, a beam aperture of F/4 defined by a cold baffle inside the camera and a band H cold filter with 1.75 µm cut-off. A background as low as 10 e/s can be measured under these conditions.

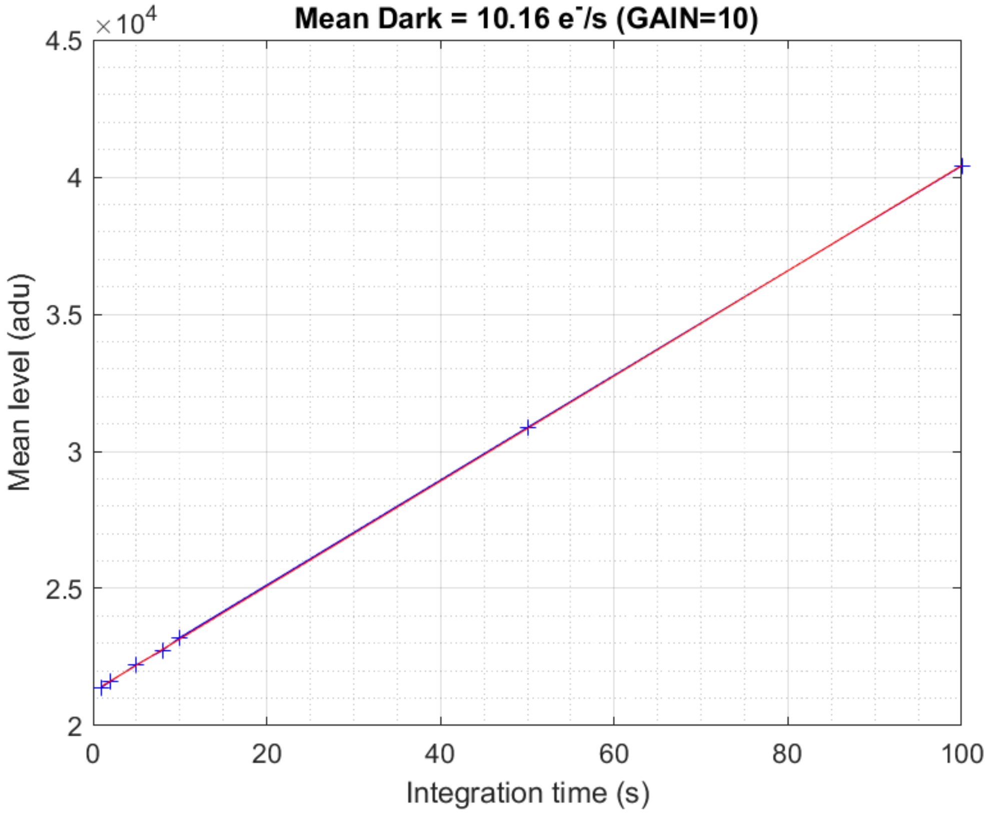


*Figure 7: C-RED One background measurement at gain x10 and 80K with a band H cold filter (1.75 µm cut-off) and a F/4 beam aperture.*

### 2.7 Guaranteed specifications

The following table shows the guaranteed specifications of the camera:

| Specification | Unit | Guaranteed specification |
|---|---|---|
| Sensor | NA | HgCdTe e-APD |
| APD polarization | V | <12 |
| Array size | Pixels | 320x256 |
| Pixel pitch | µm | 24 |
| Wavelength range | µm | 0.8 to 1.75 ; 2.5 on request |
| Operating Environmental Temperature | °C | ambient air 20°C maximum, water 35°C maximum. |
| Quantum Efficiency | % | > 60 from 1.1 to 2.4µm at 100K |
| Maximum Speed at full resolution single read | FPS | 3500 |
| Read Out Noise CDS 1750 FPS looking at a Black Body at temperature of 80 K eAPD gain x50 | e/pixel/frame | < 1 |

| | | |
|---|---|---|
| Dark Current looking at a Black Body at temperature of 80 K eAPD gain x10 | e-/s/pixel | <80 |
| Data Interface | NA | Camera Link Full |
| Optical interface | NA | T-Mount, F/4 beam aperture |
| Vacuum specification at operating detector temperature of 80K | mbar.l/s | Helium leak rate: < $10^{-9}$ mbar.l/s;<br>Closed-valve outgassing leak rate: < $10^{-4}$ mbar.l/s |
| Vibration imparted to the detector, with respect to the front flange of the Camera | µm RMS | < 1 µm RMS along each detector axis |
| Operability due to signal response | % | Pixels with signal < 0.8*median < 0.1 % at bias of 9V and integration time of 10 ms. |
| Operability due to CDS noise | % | Pixels with noise > 2*median < 0.1 % at bias of 9V and integration time of 10 ms |
| Image Full Well Capacity | e- | ≥ 6000 e- at eAPD gain of 10 |

# 3 THE C-RED 2 640X512 InGaAs SWIR camera from First Light Imaging

### Camera presentation

C-RED 2 is a high performance, high speed low noise camera designed for Short Wave InfraRed imaging based on the SNAKE detector from Lynred [6], [7], [8], [9]. C-RED 2 integrates a 640 x 512 InGaAs PIN Photodiode detector with 15 µm pixel pitch for high resolution, which embeds an electronic shutter with integration pulses shorter than 10 µs. C-RED 2 is also capable of windowing and multiple regions of interest (ROI), allowing faster image rate while maintaining a very low noise.

The software allows real time applications, and the interface is CameraLink full and superspeed USB3. C-RED 2 is designed to be updated remotely, and needs no human assistance to manage the cooling. The camera can operate in very low-light conditions as well as remote locations. Designed for high-end SWIR applications, smart and compact , C-RED 2 is operating from 0.9 to 1.7 µm with a very good Quantum Efficiency over 70%, offering new opportunities for industrial or scientific applications.


*Figure 8: Picture of the C-RED2 camera*

The Table 1 summarizes the main features and performances of the CRED-2 camera.

| Test measurement | Result | Unit |
|---|---|---|
| Maximum speed | 602 | fps |
| Mean dark + readout noise at 600 fps | < 30 | e |
| Quantization | 14 | bit |
| Detector operating temperature | -40 | °C |
| Quantum efficiency from 0.9 to 1.7 µm | > 70 | % |
| Operability | > 99.7 | % |
| Image full well capacity at low gain, 600 fps | 1400 | ke- |
| Image full well capacity at high gain, 600 fps | 35 | ke- |
| Maximum speed 32x4 window | 32066 | fps |
| Maximum speed 320x256 window | 1779 | fps |

Table 1: typical performances and main features of the CRED-2 640x512 InGaAs SWIR camera.

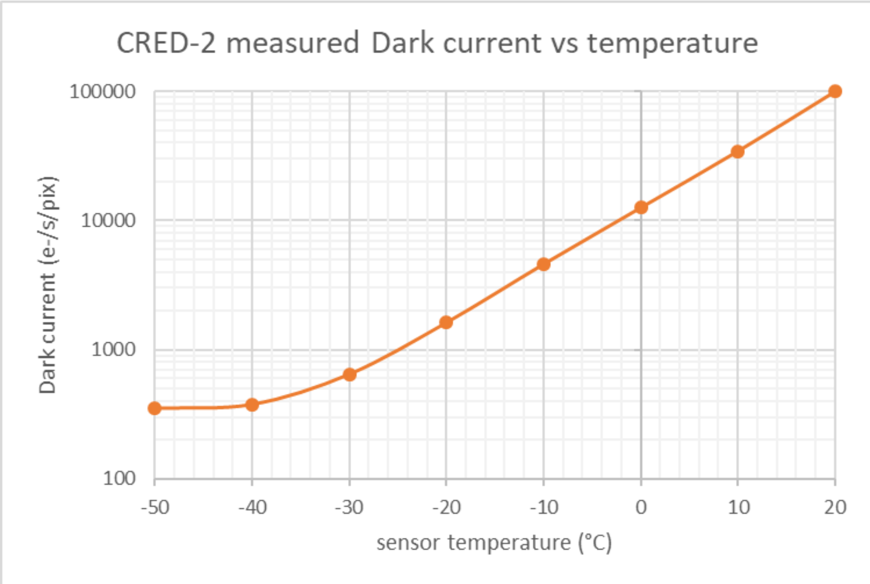


*Figure 9: C-RED 2 typical Dark (in e/s/pixel) as a function of the temperature (in °C).*

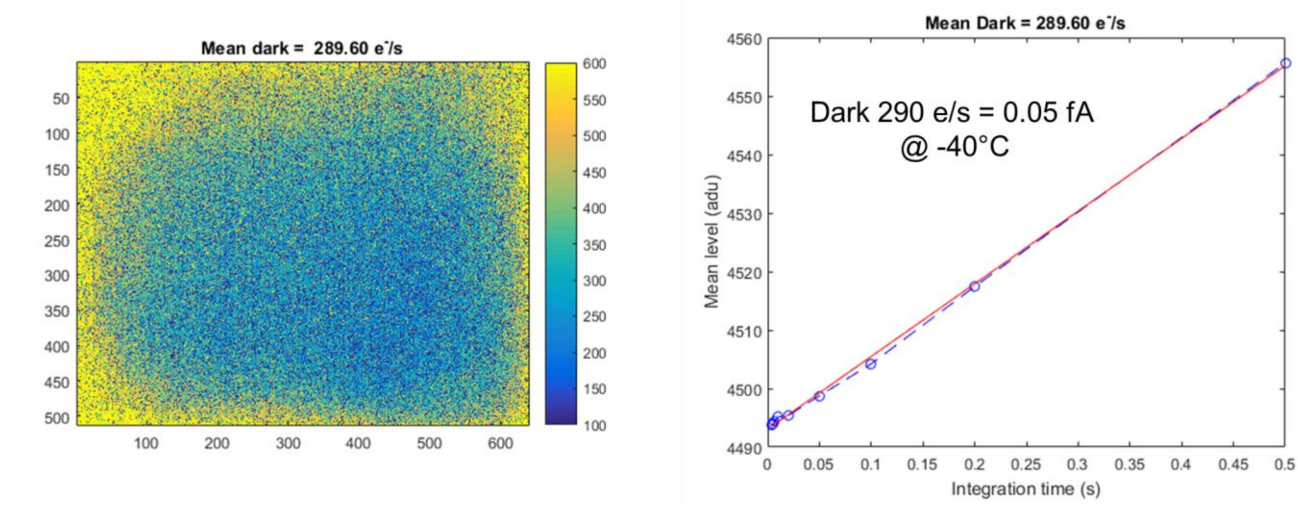


*Figure 10: (left) C-RED 2 dark image at -40°C, scale is in e/s; (right) Dark measurement at -40°C by measuring level as a function of the integration time. The camera system gain in 2.33 e/adu. Dark as low as 290 e/s (0.05 fA) is measured here at -40°C.*

The Figure 10 shows the dark current measurement from C-RED2. The mean dark current is multiplied by a factor of 2 every 7.5 °C. It also shows that a mean dark current of 290 e/s (0.05 fA) is demonstrated at an operating temperature of -40°C. The value of 290 e/s is a simple average of the dark over all the pixels from the image, deeper cooling does not show an improvement in dark suppression. This is in fact due to the backbody background of the warm detector window which sets a dark current limit that can not be overpassed .

The Figure 11 shows the total noise (readout noise + dark) of the C-RED 2 camera in CDS mode (Correlated Double Sampling) as a function of the frame rate. A total noise of 30 e- is achieved at a readout speed of 600 FPS full frame. This type of performance in terms of speed and noise combined has never been achieved so far by the C-RED 2 competitors for a SWIR InGaAs camera. When the frame rate increases, the total noise decreases while the dark signal decreases as well.

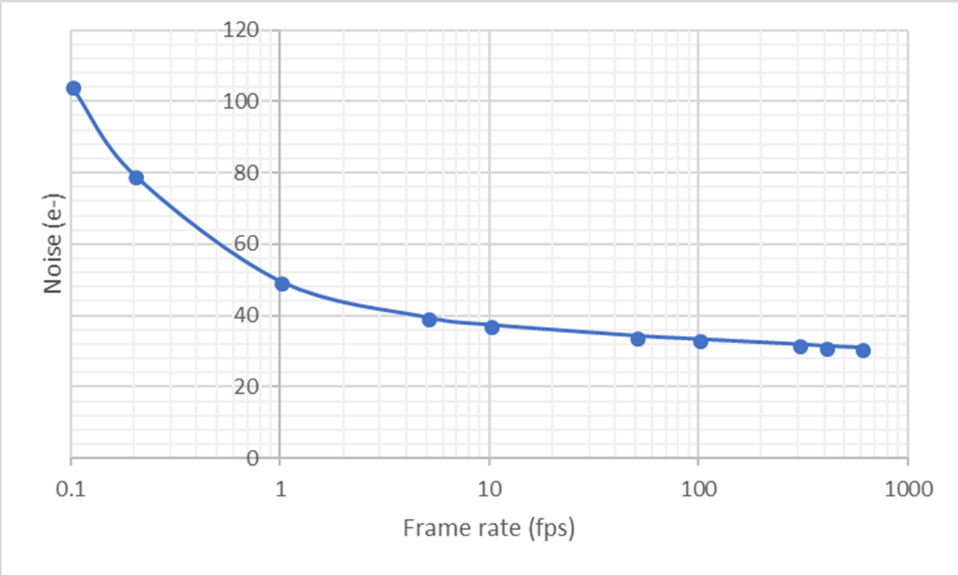


*Figure 11: C-RED2 camera dark + readout noise at -40°C full frame as a function of the frame rate.*

## 4 CONCLUSION

We've demonstrated the ability of CRED One to have comparable or even better performance than visible fast cameras dedicated to AO wavefront sensing like OCAM2 : this camera offers fast frame rate, subelectron noise, low background, wide spectral response over J, H and K bands, and outstanding cosmetics compared to other SWIR cameras. APD technology is now mature enough to be used in scientific applications. An unprecedented noise of 0.2 e was achieved for a SWIR camera at the speed of 1720 FPS with CDS readout. C-RED one permits then a significant advance in short wave infrared imaging and is opening new windows for scientific applications like IR wavefront sensing or fast IR focal plane arrays used in astronomy.

In addition to the C-RED One development, C-RED 2 is InGaAs 640x512 fast camera with unprecedented performances in terms of noise, dark and readout speed based on the SNAKE SWIR detector from Sofradir. A readout noise of 30 e has been obtained at 600 FPS readout speed in CDS mode. Cooled at -40°C, the C-RED 2 camera is able to achieve a dark current of ~300 e/s (0.05 fA).

C-RED One and C-RED 2 are both SWIR commercial cameras from First Light Imaging fully available and in production now.

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