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C-RED 2 InGaAs 640x512 600 fps infrared camera for low order wavefront sensing

Philippe Feautrier[a,b,*], Jean-Luc Gach[a,c], Stephane Lemarchand[a], Fabien Clop[a], Thomas Carmignani[a], Yann Wanwanscappel[a], Eric Stadler[a,b], David Boutolleau[a] and Carine Doucouré[a]

[a]First Light Imaging S.A.S., Europarc Sainte Victoire, Bat 6, Route de Valbrillant Le Canet, 13590 Meyreuil, France;
[b] Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France ;
[c] Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388 Marseille, France;

*philippe.feautrier@first-light.fr; phone +33 442612920, www.firstlight.fr

ABSTRACT

Infrared wavefront sensors are now implemented in MCAO systems as reference (or truth sensors). After the successful development of C-RED One, the only commercial 320x256 3500 fps e-APD sub-e noise infrared camera, First Light Imaging developed the C-RED 2 InGaAs 640x512 fast camera with unprecedented performances in terms of noise, dark and readout speed based on the SNAKE SWIR detector from Sofradir. The C-RED 2 characteristics and performances at 600 fps are fully described in this paper.

The C-RED2 development is supported by the "Investments for the future" program and the Provence Alpes Côte d'Azur Region, in the frame of the CPER.

Keywords: infrared camera, high speed, low noise, InGaAs, SWIR, 640 x 512 InGaAs, non-destructive readout.

1. INTRODUCTION

Near-infrared (NIR) tip-tilt sensor based on multiple reads of a small region (e.g. 4x4 pixels) of a HgCdTe infrared based camera has been reported in the past by several authors. For this application, the full image is used first to locate the infrared guide start, and then the detector is used in windowed mode to sense fast tip-tilt mode. Infrared wavefront sensors are today implemented in MCAO systems as reference (or truth sensors). In the case of the ELT-MAORY instrument, the Low Order and Reference (LOR) Module is implementing the Natural Guide Star Wavefront sensing functionalities needed by MAORY in MCAO mode. It consists of 3 identical LOR WFS units to sense the aberrations in the direction of 3 NGSs. The Low-Order WFS is required to measure 5 modes at 500Hz. In this regime, the analysis shows that the best configuration is a Shack-Hartmann sensor with 2x2 subapertures operating in the H band. All these design studies for MCAO clearly show the increasing interest of fast low noise infrared camera in complement of the LGS wavefront sensors of a MCAO system.
After the successful development of C-RED One, the only commercial 320x256 3500 fps e-APD sub-e noise infrared camera, First Light Imaging developed an InGaAs 640x512 affordable fast camera with unprecedented performances in terms of noise, dark and readout speed based on the SNAKE SWIR detector from Sofradir. The camera was called C-RED 2. The C-RED 2 characteristics and performances are described herefater.
Thanks to its state of the art electronics, software, and innovative mechanics, C-RED 2 is capable of exceptional performances: exceeding 600 images per second with a read out noise from 20 to 30 electrons. To achieve these performances, 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.

C-RED 2 is the only InGaAs existing camera offering such characteristics and such level of performances, allowing use for scientific applications like NGS infrared wavefront sensing.
The C-RED2 software allows real time applications, and the two possible data interface of the camera are CameraLink full and superspeed USB3. C-RED 2 needs no human assistance to manage the cooling. The camera firmware can be remotely up-dated by simply connect the camera on internet. The camera can operate in very low-light conditions as well as remote locations. The camera cooling is autonomous and does not need liquid cooling offering very easy implementation on a telescope. 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. The large number of pixels of the camera and the windowing capabilities with line fitting non-destructive readout mode implementation allows the use of the two AO modes described above. The camera, first designed to run at 400 fps full frame, is now reaching amazing frame rates of 600 fps for a 640x512 full frame CDS mode readout. The non-destructive readout mode allows to decrease the readout noise down to 20 e while the windowing capabilities allows super-speed frame rates on demand.
The 640x512 pixel size of C-RED2 can potentially be used to sense the whole NGS pratol field at the same time and avoid moving the NGS arms. This option decreases the differential flexures between the infrared NGS increasing the mechanical stability of low order WFS system.

2. 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 Sofradir [1], [2], [3], [4], [5], [6]. 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 (see Figure 1), 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 1: Picture of the C-RED2 camera

The Table 1 summarizes the main features and preliminary 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	43	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.

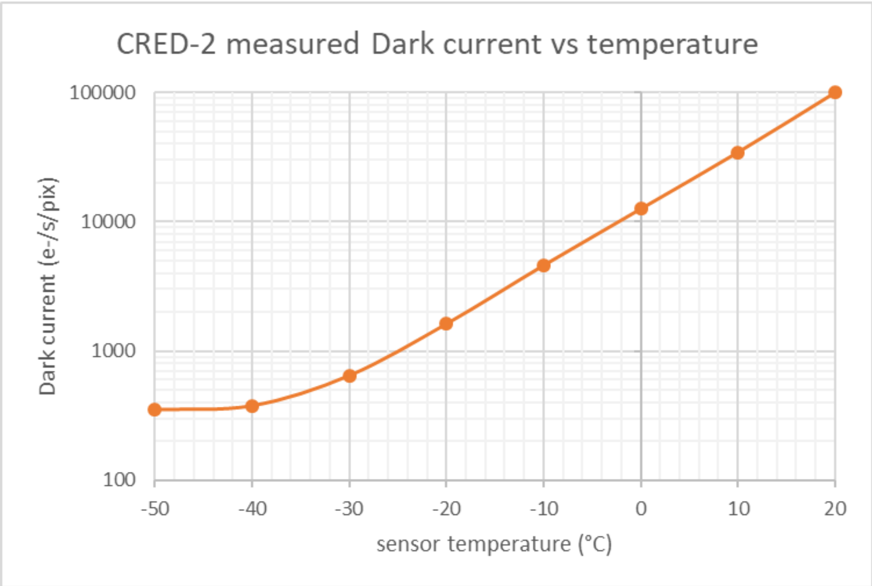

Figure 2 : C-RED 2 typical Dark (in e/s/pixel) as a function of the temperature (in °C).

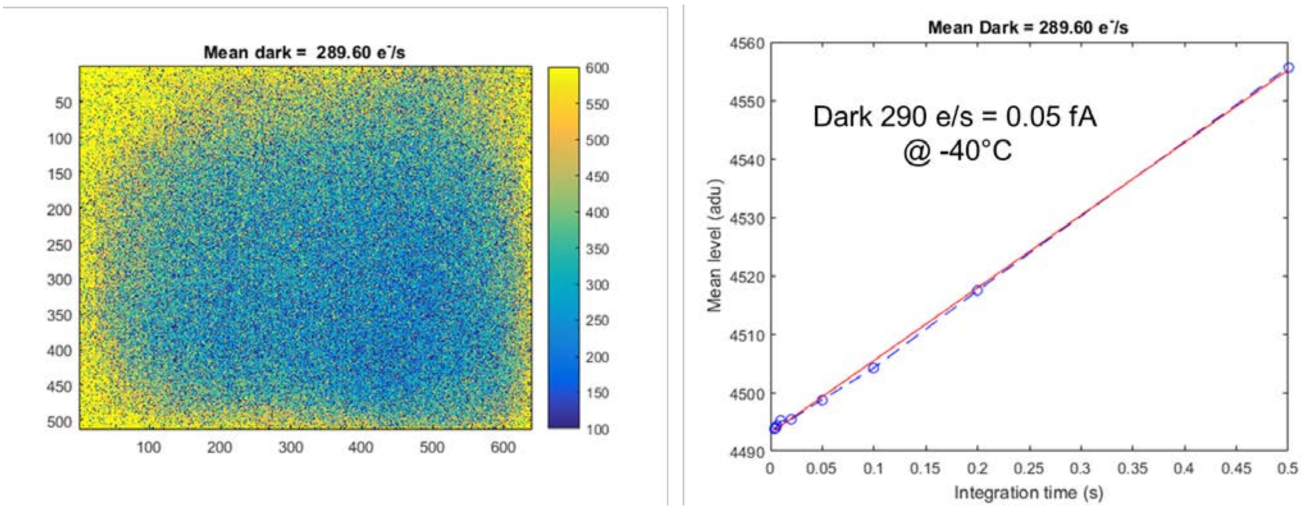

Figure 3: (left) C-RED 2 dark image at -40°C, scale is in e/s; (right) Dark measurement at -40°C by measuring level as a function of the integration time. The camera system gain in 2.33 e/adu. Dark as low as 290 e/s (0.05 fA) is measured here at -40°C.

The Figure 2 and Figure 3 show 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 4 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.

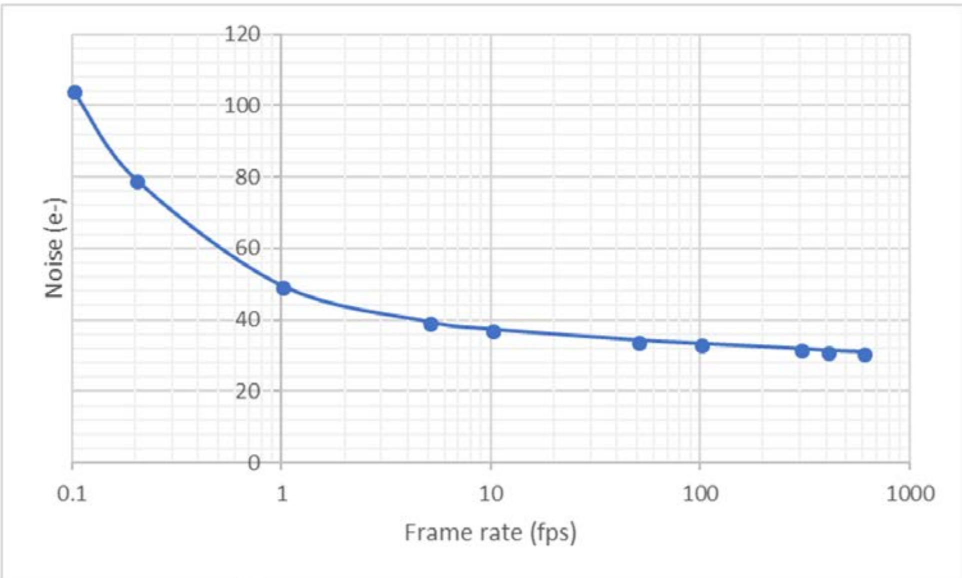

Figure 4: C-RED2 camera dark + readout noise at -40°C full frame as a function of the frame rate.

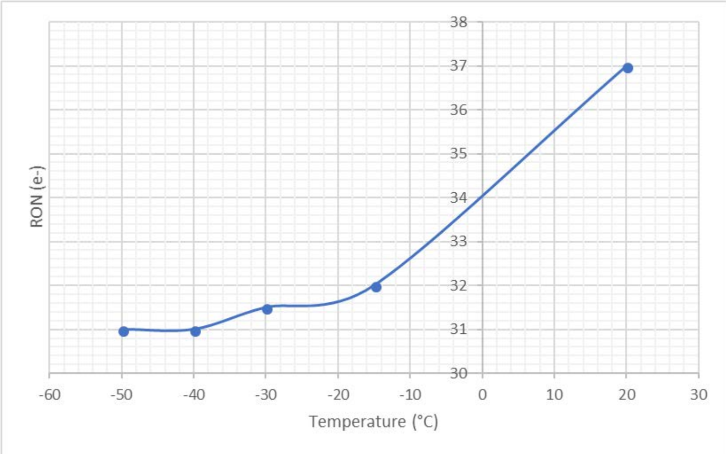

Figure 5: readout noise in CDS mode at 400 fps for various temperature

The Figure 5 shows the readout noise variation with the temperature, demonstrating that the readout noise decreases with the temperature. Decreasing the temperature below -40°C is not useful to decrease the readout noise.

Non destructive readout mode (NDR)

It is possible to perform non-destructive readouts to decrease the readout noise of the camera. The intensity of each pixel is then computed by linear fitting or Fowler sampling. The impact is a frame rate decrease to do the computation over the selected images. Sampling-up-the-ramp (or line fitting) with IR detectors was first introduced by Fowler and Gatley in 1991 [7], [8]. The authors reported the noise reduction of infrared detectors by multiple reads of the signal. At that time, the authors reported an improvement of the readout noise by a square root of N for the line fitting methode where N is the number of multiple readout. In fact, the real noise equations were studied in details by M. Roberto in 2007 for the Space Telescope Science Institute [9]. In this report, Roberto distinguished the 2 types of ramp signal sampling: the "up to the ramp" sampling is the linear fit of the signal ramp, sampled at the frame frequency of the camera. The integrated signal is given by the slope of the ramp multiplied by the number of reads N. The second way to sample the ramp is to use the

Fowler sampling: Fowler readout is done by reading several times the signal at the beginning and at the end of the integration, and averaging down the results. The author demonstrated that the readout noise reduction of the Fowler sampling is the square root of N while for the line fitting sampling, the noise reduction is less favorable and is equal to $\sqrt{N/12}$.

More precisely, for the up-to-the-ramp method (line fitting), the readout noise scales as $\sigma_{ron\,N}=\sqrt{\frac{12N}{(N^2-1)}}\,\sigma_{ron}$ if $\sigma_{ron\,N}$ is the readout noise after line fitting of the N readouts while σ_{ron} is the readout noise of a single read. For N>7, this equation shows that the line fitting method start to ne less noisy than the CDS readout.

When the noise is Poisson limited, the author shows that the noise can be given by:

$$\sigma_{poisson}=\sqrt{\frac{6}{5}\frac{N^2+1}{N^2-1}}\sqrt{F.T_{int}(N)}$$

Where F is the background flux and $T_{int}(N)$ in the integration time after the N readouts. With a quadratic sum of the 2 previous equations, one can estimate the theoretical noise in all cases.

The higher N is, the lower the readout noise is but the higher the Poisson limited noises increases with the integration time, showing that the total noise for the line fitting method has an optimum N which depends on the single read noise and the dark flux.

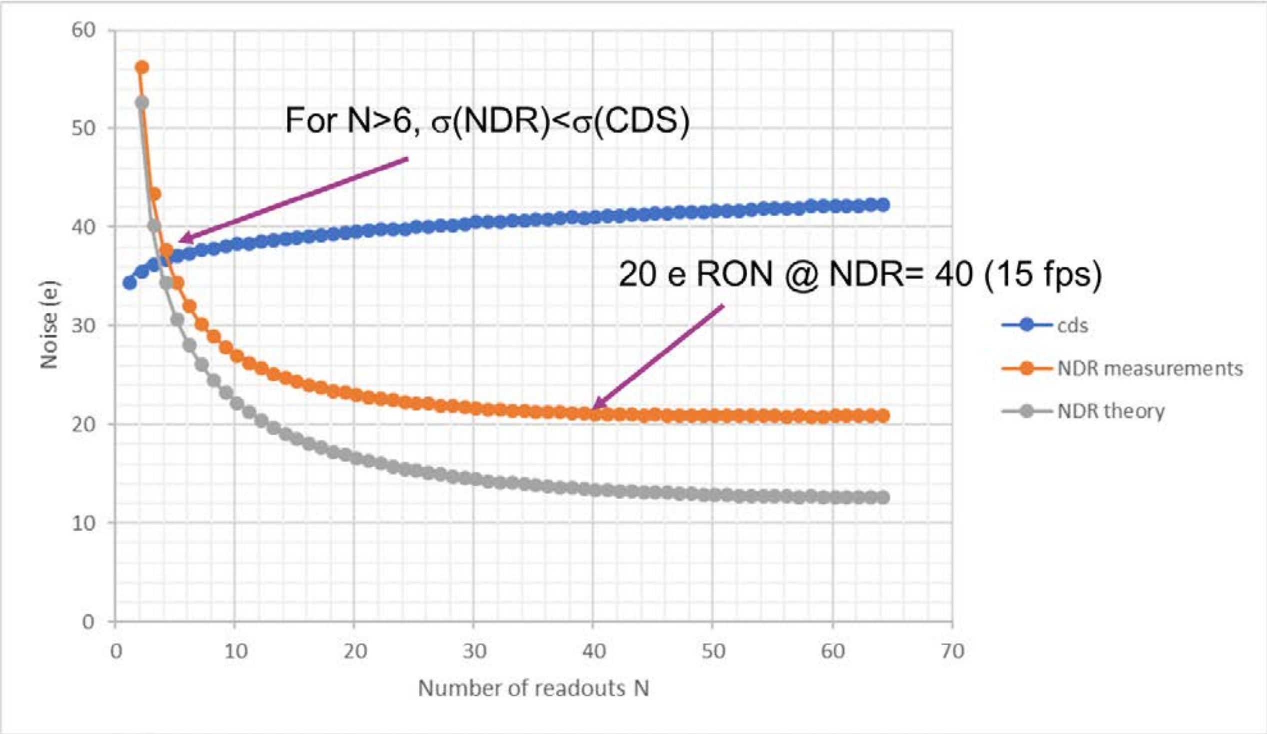

Figure 6: readout noise comparison for the full frame readout of C-RED 2 at 600 fps between the CDS mode and the non-destructive readout mode for an equivalent integration time. The theory is also shown in the figure.

The Figure 7 compares the readout noise for non-destructive readout to the CDS noise, full frame, at 600 fps readout. This figures shows that in these conditions, the non-destructive is less noisy than the CDS readout when the number of readouts.is higher than 6, which is very close to the theory. The theoretical curve shown on this figure shows less noise compared to what we measure, showing that there is some additional noise to this simple model.

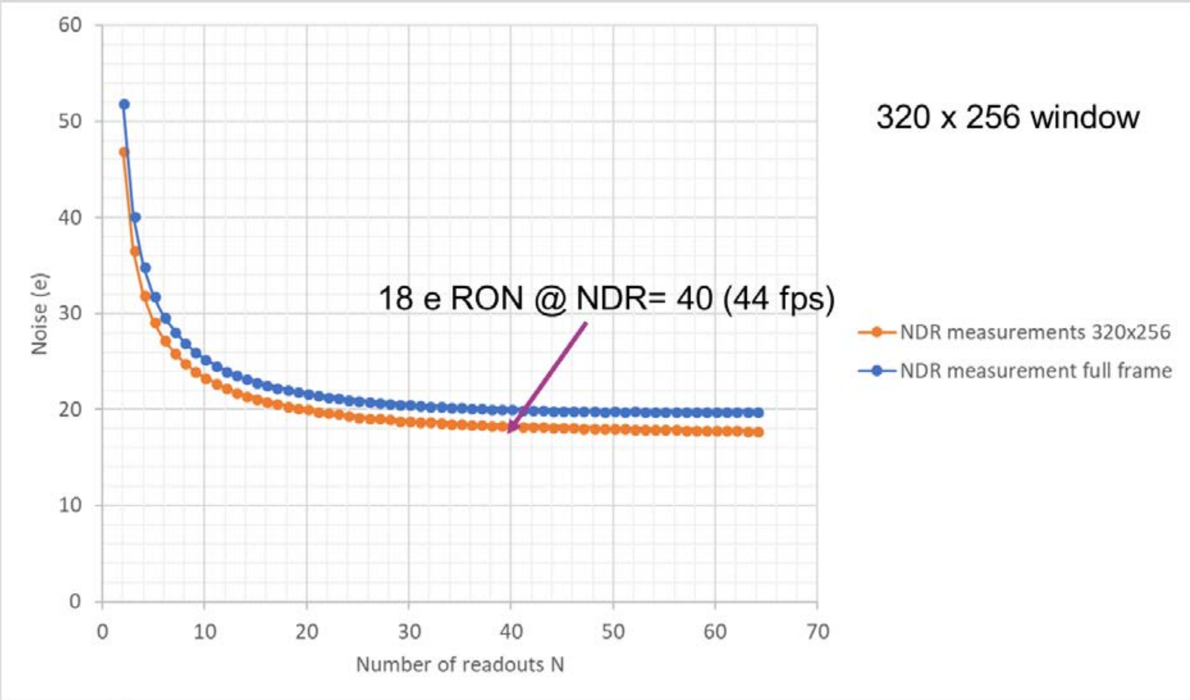

Figure 7: for non-destructive readout, comparison between the full frame readout and a 320x256 window readout (1779 fps).

When the windowing readout mode is used, then the frame readout is higher and the dark noise is lower. This is shown clearly in the Figure 7. For a window of 320x256 pixels, a readout noise of 18 e can be achieved with N=40 readouts for an equivalent frame rate of 1779/40 = 44 fps.

What must be noticed is that the computation of the line fitting is done internally using the camera FPGA. Therefore the use of the NDR mode is transparent to the user which has a direct access to the integrated signal obtained by line fitting. This allows also to compute the temporal readout noise as if it was a simple CDS readout.

Windowing mode and frame rates at 600 fps full frame CDS readout

		Columns						
		32	64	128	256	320	512	640
Lines	4	32066	31512	30458	28548	27680	25367	24029
	8	28108	27348	25945	23532	22486	19840	18397
	16	22542	21631	20015	17413	16350	13819	12526
	32	16147	15254	13736	11455	10577	8599	7646
	64	10302	9596	8440	6801	6199	4898	4297
	128	5975	5509	4765	3752	3391	2632	2291
	256	3247	2975	2547	1978	1779	1367	1184
	512	1697	1549	1319	1016	912	697	602

Table 2: windowing mode frames rates for 600 fps readout full frame

The Table 2 shows the C-RED frame rates in windowing mode when the full frame readout is 602 fps. Frame rates as high as 32066 fps can be obtained for a 4x32 pixels window.

3. CONCLUSION

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 total noise (readout + dark 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). A noise of 20 e- is obtained in in non-destructive readout full frame at 15 FPS (40 readouts). A noise of 18 e is obtained in non-destructive readout with a 320x256 window at 44 FPS (40 readouts).

The use of non-destructive readout is embedded in the camera and is transparent to the user, as well as the flat/bias image correction on the fly.

The 600 fps version of C-RED 2 is now commercially available at First Light Imaging [10]. The upgrade of the 400 fps version of C-RED 2 to the 600 fps version is possible remotely.

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