sCMOS

ON THE CUTTING EDGE

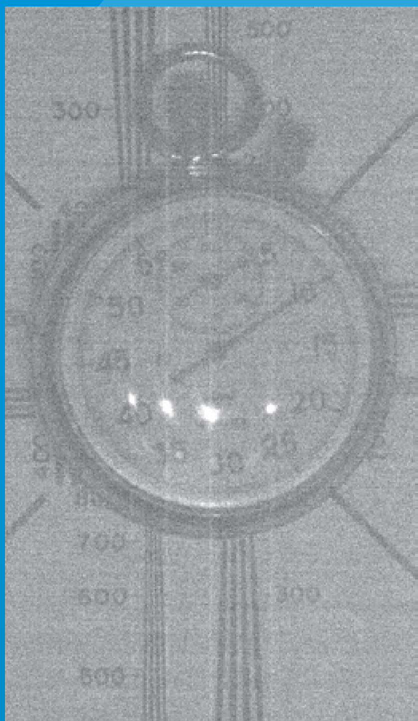
pco.edge family

pco.

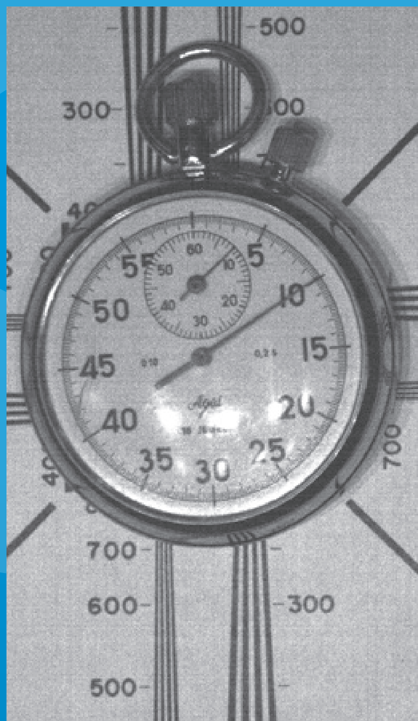
pco.edge - scientific CMOS

CUTTING EDGE IMAGING

The pco.edge camera utilizes a scientific CMOS (sCMOS) image sensor to offer a combination of outstanding features. An impressive combination of low readout noise of 1.1_{med} electrons, high resolution of 2560 x 2160 pixels, a maximum frame rate of 100 frames/s and a high dynamic of 1 : 27 000 make this camera an ideal choice for a wide variety of applications. In addition, the pco.edge provides an excellent homogeneous pixel response to light (PRNU, photo response non-uniformity) and homogeneous dark signal pixel behavior (DSNU, dark signal non-uniformity). This is achieved by taking advantage of sophisticated (FPGA based) electronic circuit technology and firmware algorithms. These outstanding qualities are clearly visible when one compares images under the same low light conditions. The two monochrome images (see photos) show a simple setup with a stopwatch under low light conditions.
The left image was taken with a scientific grade, cooled CCD camera (at -5 °C) at similar exposure conditions to the sCMOS image. The right image was taken with a sCMOS pco.edge camera (at +5 °C), which demonstrates superior image quality. Also, as it is a sCMOS image, no smear (vertical bright lines in the left image due to bright reflections) occurs in the image.



scientific interline CCD



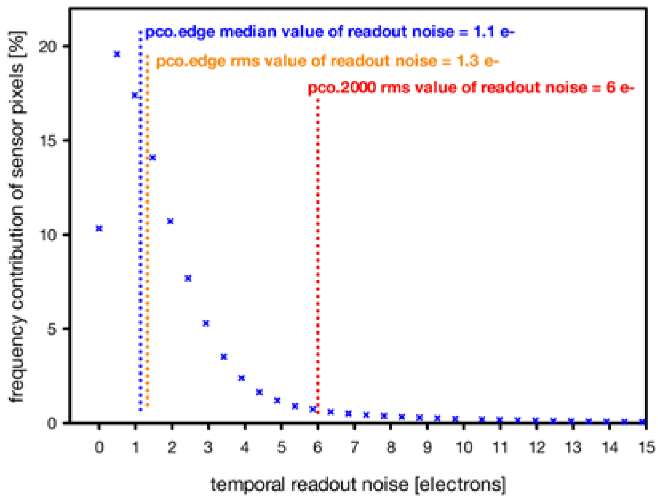
scientific CMOS

DISCOVER THE POSSIBILITIES

Scientific CMOS image sensors enable new application areas for scientifc imaging, including structured illumination and localization microscopy, dynamic processes in fluorescence microscopy, high contrast imaging in 3D metrology, particle image velocimetry, digital pathology, and a myriad of other imaging solutions.

AT PCO AG
INNOVATION IS ATTITUDE -
SINCE 1987.

LOW READOUT NOISE



Histogram of the readout noise values in a pco.edge camera. The frequency contribution of the noise values is given as a percentage of the total number of CMOS image sensor pixels. The vertical lines denote key readout noise values for the pco.edge and pco.2000 cameras.

The upper image shows a typical fixed pattern noise in a CMOS image sensor, which is caused by small differences of the column amplifiers of the sensor. The lower image shows the corresponding image of the scientific CMOS pco.edge camera at + 5°C sensor temperature with the standard FPGA based calibrated dark image.

The sCMOS image sensor in the pco.edge features extremely low readout noise, which has never previously been achieved in combination with the parameters of high frame rates, high quantum efficiency and high resolution. This results in a very low detection limit and an impressively high dynamic.

TEMPORAL READOUT NOISE

The term temporal readout noise is used to describe the total of all unwanted signal contributions and varies from image to image over time. For clarity, it is generally assumed that an image sensor or a camera can be best described by a linear model approach (see also the EMVA 1288 standard[1] for a detailed explanation of such a model). For practical purposes, the readout noise defines the minimum light level of the input signal, which is required to generate an useable image. The camera's overall readout noise consists of various image sensor noise, as well as contributions from the camera itself. Examples of readout noise include: kTC-noise, Johnson noise, 1/f noise, dark signal noise, spurious noise and others.

LOW READOUT NOISE

The biggest advance of the new sCMOS image sensors is the reduction of the readout noise down to levels of 1.1_{med} / 1.3_{rms}[2] e^-, which has opened the area of scientific imaging applications for CMOS sensors.

The major improvements in these new concept CMOS image sensors are noise optimizations at two locations within the pixel structure. The pixel's noise dominating capacitor in a pixel has been reduced to the smallest possible level and with the simultaneous dual gain readout design, the two 11 bit A/D-converters are operated at lower frequencies, minimizing the 1/f-noise, while maintaining a high frame rate. In comparison, the noise contribution of one fast 16 bit A/D converter would be higher.

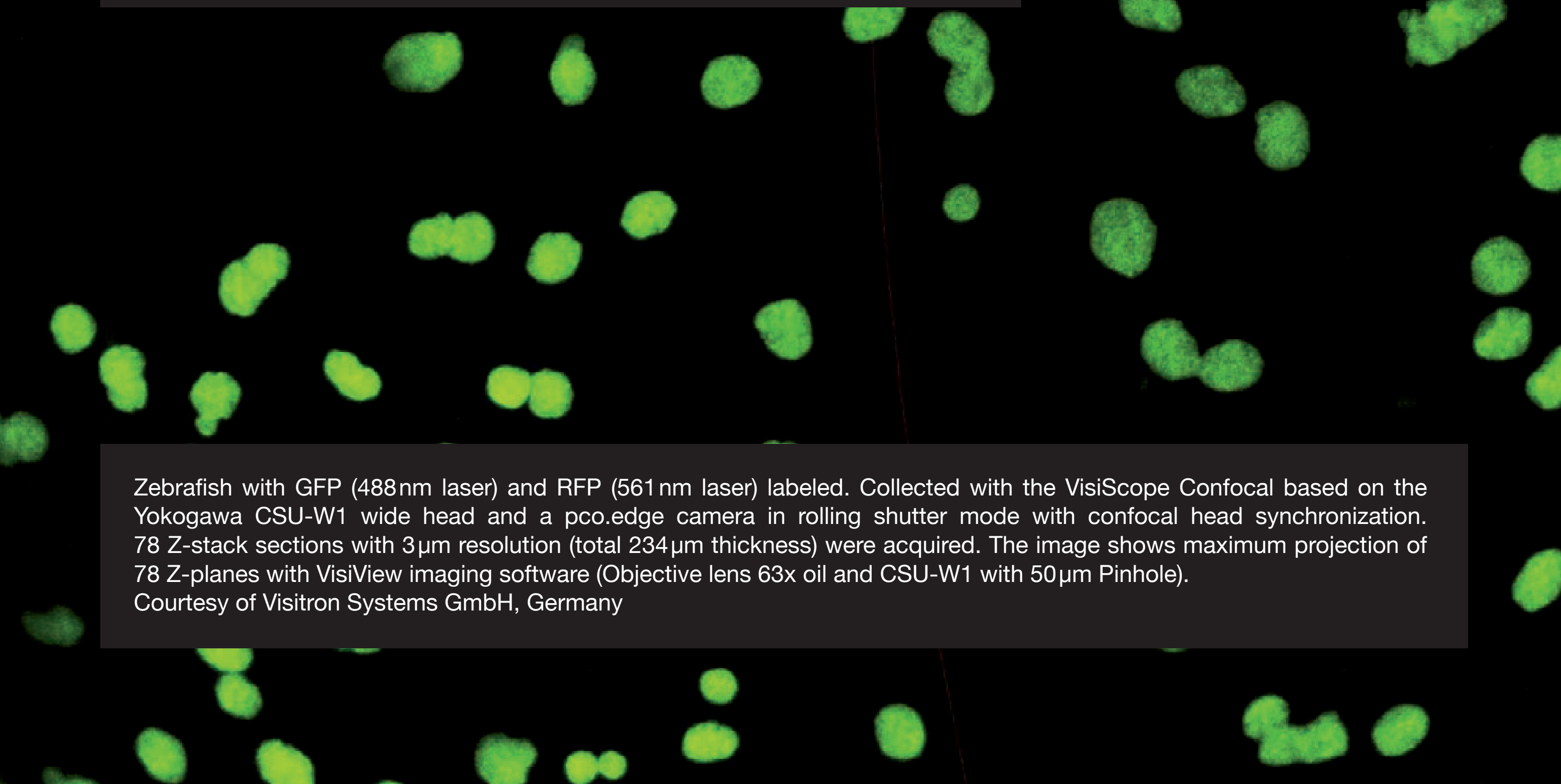
READOUT NOISE EVALUATION

This temporal readout noise is usually measured as the difference between two consecutive dark images. The result image corresponds to the variance. The value of the readout noise will depend on the noise distribution model used. The above histogram is representative of a typical pco.edge camera. It is possible to use either a Gaussian or a Median evaluation. Since the histogram is not symmetrical either approach can be used, with the Median fit expressing the smaller readout noise value. For comparison a readout noise value for a cooled scientific interline CCD camera (pco.2000) is included in the graph as well. More than 95 % of all pixels of the pco.edge camera have readout noise values smaller than 3 e^-. It should be noted that the histogram has calculated values, which explains the presence of noise values with fractions of electrons.

SPATIAL READOUT NOISE

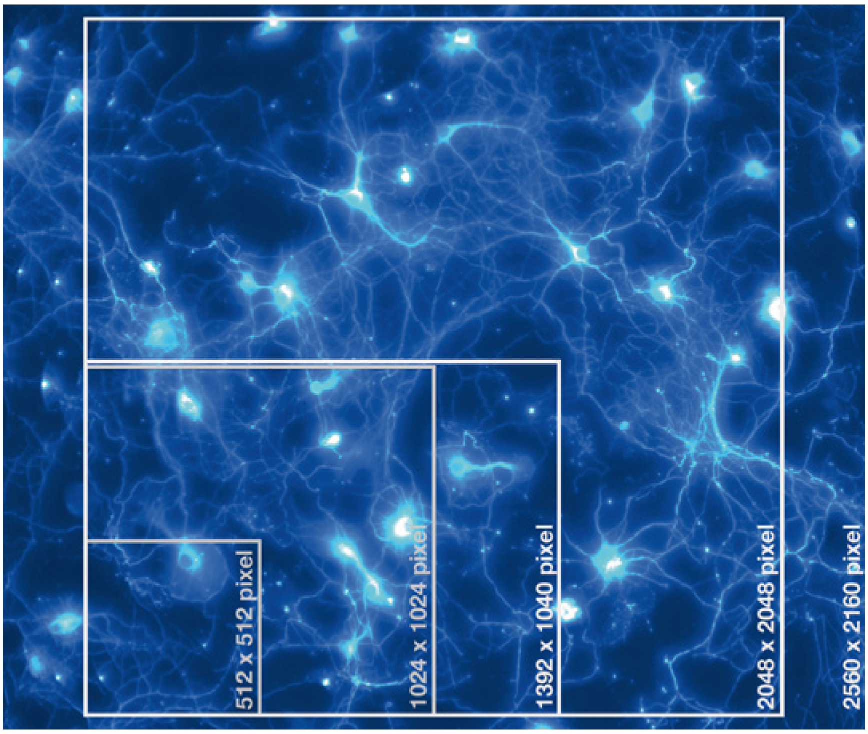
In addition to temporal noise, which is usually abbreviated as readout noise, there is also spatial readout noise present in CMOS image sensors. This spatial readout noise is caused by very small differences between column amplifiers. Most CMOS image sensors have one or two amplifiers per column, which convert the light induced charge carriers into voltages. There are two different fractions distinguished. The first fraction is dark fixed pattern noise (FPN, see images on opposite page), which is defined as dark signal non-uniformity (see EMVA 1288 standard, DSNU$_{1288}$[1]), measured in dark images. The second can be seen in bright field, where differences in the gain of these amplifiers might occur, which is measured and defined as photo response non-uniformity (see EMVA 1288 standard, PRNU$_{1288}$[1]).

[1] http://www.emva.org/cms/upload/Standards/Stadard_1288/EMVA1288-3.0.pdf
[2] the index med refers to a median fit evaluation of the readout noise histogram, while the index rms assumes a Gaussian fit with a root mean square evaluation



Zebrafish with GFP (488 nm laser) and RFP (561 nm laser) labeled. Collected with the VisiScope Confocal based on the Yokogawa CSU-W1 wide head and a pco.edge camera in rolling shutter mode with confocal head synchronization. 78 Z-stack sections with 3 µm resolution (total 234 µm thickness) were acquired. The image shows maximum projection of 78 Z-planes with VisiView imaging software (Objective lens 63x oil and CSU-W1 with 50 µm Pinhole).
Courtesy of Visitron Systems GmbH, Germany

RESOLUTION



The large resolution of the new sCMOS image sensor in the pco.edge camera opens up new applications. The resulting large field-of-view achieved by the pco.edge camera will require fewer scanned images, dramatically increasing recording speeds. The image of neurons with fluorescent calcium staining shows the 2560 x 2160 pixels (5.5 Megapixels) resolution of the sCMOS image sensor versus a variety of common scientific image sensor formats. The smaller two frames correspond to the standard emCCD resolutions of 512 x 512 pixels and 1024 x 1024 pixels, while the larger two frames correspond to popular scientific interline CCD resolutions of 1392 x 1040 pixels and 2048 x 2048 pixels. The difference in the available field-of-view is clearly seen.
It should be noted that this resolution comparison assumes that the optics are adapted to correct for different pixel sizes between the image sensor formats.

PIXEL SIZE

A common misconception assumes that larger pixels are more sensitive. In applications where higher resolution is needed, the new camera should replace the old camera under the same optical conditions. The goal to have more resolution, let us say for example 4-times as much, can be achieved if the the pixel size of the image sensor in the new camera is one-fourth of the area of the old camera. Geometrically, this means the new pixels cover one-fourth of the area of the old pixels. Therefore, the new pixels geometrically can collect one-fourth of the signal, which means a smaller signal per pixel.

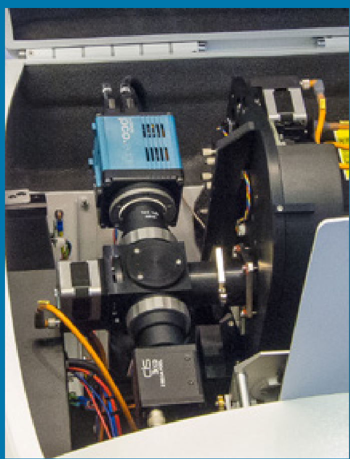
However, this is a feature of the application and not of the image sensor. Therefore, it is correct that a smaller signal is measured, because of the nature of the optical situation, but it is not related to the sensitivity of the image sensor.

OPTICS

In order to replace a camera in an existing application set-up with a higher resolution camera, like the pco.edge, one must adapt the optics, as well as the illumination. In case of microscopes, in the past, film cameras with F-mount adapters were used to expose slide film. Recently, this has changed to the use of smaller C-mount adapters for cameras with smaller image sensors. It is possible to use the pco.edge camera with a C-Mount adapter, but it requires appropriate optics to completely realize the benefit of its full resolution.

SIZE MATTERS

The pco.edge scientific CMOS camera is the smallest sCMOS camera on the market. It allows OEM system integrators to take advantage of its small footprint, saving valuable space. The water-cooled version of the pco.edge camera is slightly larger to accomodate the input and output water fixtures.



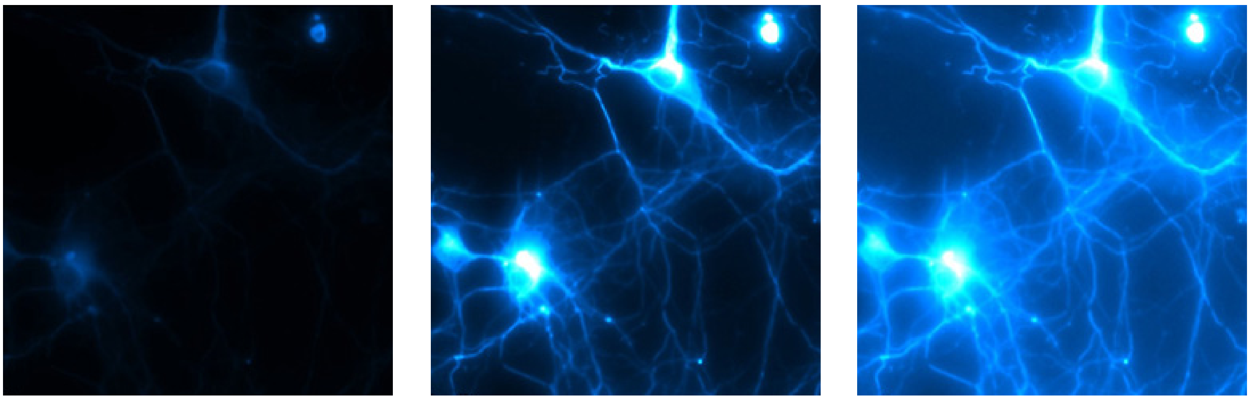
The pco.edge sCMOS camera in the Pannoramic 250 Flash slide scanner by 3DHistech, Budapest,Hungary.

“Our experiments require high temporal and spatial resolution, but at the same time we do not want to compromise about fluorescence sensitivity. So we were looking for a camera, like the pco.edge, which provides both - high frame rates and the ability to image weakly fluorescent samples.”

Prof. Dr. Sarah Köster, Institute for X-Ray Physics, Georg-August-University, Göttingen, Germany

"We choose the pco.edge because it provides very low noise, very high dynamic range and all this at high speed. This is simply the best available camera for fluorescent slide scanning."

Dr. Viktor Varga, CTO 3DHistech Kft., Budapest, Hungary



[a] [b] [c]

The same extract of a larger image of neurons with a fluorescent marker for Calcium with different scaling to the 8 bit world: [a] the image is displayed with a linear scaling from 16 bit to 8 bit => *the image looks very dark, nearly under-exposed*, [b] the image is displayed with a minimum – maximum scaling with maximum to 8 bit => *more structures and information become visible*, and [c] the image is displayed with a non-linear scaling from 16 bit to 8 bit using a different gamma value => *the image looks well exposed and a lot of structures are visible*.
For all evaluations, it has been the same image! It is important that high dynamic images are properly displayed.

DYNAMIC

An image sensor's general parameter dynamic refers to its intra-scene dynamic and is different than the parameter pixel dynamic.

INTRA-SCENE DYNAMIC

The (intra-scene) dynamic describes the contrast or the range between the brightest and the darkest spot in an image. So, what range of light levels can be detected by the image sensor? The answer or the value depends on two parameters that are characteristical of each image sensor. First there is the smallest signal, which can be detected. To be detectable, the minimum signal must be larger than the readout noise; therefore the readout noise is the smallest detectable unit. The maximum signal corresponds to the fullwell capacity of the image sensor. Both values allow determination of the image sensor's dynamic:

$$\text{dynamic} = \frac{\text{fullwell capacity}\left[e^-\right]}{\text{readout noise}\left[e^-\right]}$$

For the pco.edge camera the dynamic dyn can be expressed as follows:

dyn = 30000 [e^-] / 1.1$_{med}$ [e^-] = 1 : 27000

If one half bit of uncertainty for Analog / Digital Converters is taken into account, it is reasonable to offer 16 bit images (65536 light levels) in the pco.edge sCMOS camera. In general, the dynamic can only be improved either by lowering the image sensor's readout noise or by increasing its fullwell capacity.

PIXEL DYNAMIC

In contrast, the pixel dynamic is described by the pixel's maximum possible signal-to-noise-ratio (SNR), which occurs at fullwell or saturation. Since the noise behavior of the electrons corresponds to the photon noise, the maximum SNR is given by:

$$\text{pixel dynamic} = \frac{\text{number of electrons}\left[e^-\right]}{\sqrt{\text{number of electrons}\left[e^-\right]}}$$

For the pco.edge camera this means: pixel dynamic = 1:173.2. This value can only be improved by increasing the image sensor's fullwell capacity.

BENEFIT OF DYNAMIC

The benefit of a higher dynamic is the possibility of greater information content, which is a larger number of detectable light levels and resulting gray levels in a monochrome image. But what does this mean? In all signal ranges in the image, a finer gradation is possible, especially with a high contrast object or sample. This can range from fluorescent markers in high contrast biological samples to applications that measure un-cooperative (highly reflecting) metrology surfaces. Therefore, it can be possible to resolve low-contrast structures in high contrast images. Obviously, this is only an advantage, if the application, the object, the sample or the situation represents a scene with a high dynamic.

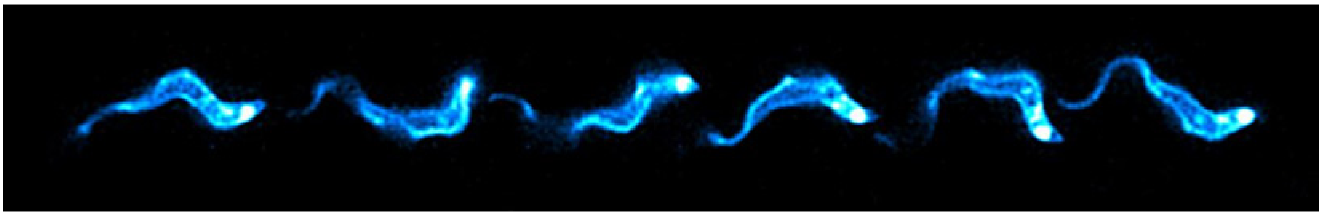
TO LOOK AT HIGH DYNAMIC IMAGES

This can be a challenge, since we are basically living in an "8 bit world". As the most that untrained human eyes can distinguish is approximately 256 gray levels (except for example trained radiologists, who can go up to 9-10 bit), all of the display devices like TV screens, computer screens, printers just use and display 256 levels. This can be a problem, if a 16 bit image, like one created by the pco.edge camera with its sCMOS image sensor, is opened by an image viewer or any software with image processing, because an image with potentially 65536 gray levels should be displayed with just 256 gray levels.

Let's assume that there is an image that is only illuminated up to 30 % of the full scale. This would result in a maximum of 19660 gray levels. If such an image were opened in an image viewer, the viewer would recognize the 16 bit TIFF format. The viewer would linearly scale down the image, such as 0 in a 16 bit image corresponds to 0 in the 8 bit image display screen and 65535 in a 16 bit image corresponds to 255 in the 8 bit image display screen. The result can be seen in image [a] in the figure on the opposite page.

The image looks under-exposed with insufficient information, which is actually not the case, since there is much more information present in the image. The same image, when scaled with a minimum – maximum scaling, means that the minimum in the 16 bit image corresponds to 0 in the 8 bit image display screen and the maximum in the 16 bit image corresponds to 255 in the 8 bit image display screen. In the figure on the opposite page, image [b] shows much more details compared to image [a], but it is still the same image; nothing but the way it is displayed has changed. Recalling the real numbers, the information content has been reduced to 8 bit. Image [c] in the figure on the opposite page shows even more of the fine neuron network in an 8 bit display (in this case by changing the gamma value). This is a final option to show as much as possible from the 16 bit values in the 8 bit world of screens and publications.

HIGH SPEED



An image sequence a fluorescence labeled single trypanosome, recorded with a pco.edge sCMOS camera at 200 frames/s (false color rendering).

The term "high speed camera" is usually referring to a camera system that is capable to record an image sequence at a high image or frame rate. Whether a camera is considered a high speed camera, is more related to the application and the human eye. Usually, a camera that can record 1000 frames/s with a resolution of 1000 x 1000 pixels is considered to be a high speed camera.
However, these cameras have readout noise values that are 10- 20 times larger than a sCMOS camera like the pco.edge.

Previously, in life science applications, low speed or "slow-scan" camera systems were used to overcome low light conditions. For these applications, low light performance in combination with a full frame (2560 x 2160 pixels) rate of 100 frames/s of the pco.edge or 200 frames/s at full HD resolution (1920 x 1080 pixels) can be considered as high speed. This allows the camera to be used in a wide variety of life science applications.

HIGH FRAME RATE

In new micrsocpy methods such as localization / super resolution microscopy and structured illumination microscopy, the high frame rate leads to a result image more quickly. Instead of taking minutes to receive a super resolution image, it is now possible to get the image within seconds.

HIGH THROUGHPUT

In scanning applications such as digital pathology or spinning disk confocal microscopy, the high frame rate significantly reduces the overall image recording time. This enables higher throughputs to achieve a greater number of results in a shorter time. In life science and pharmacology, the pco.edge sCMOS camera is ideal for integration into systems that accomplish routine lab tasks.

FRAME RATE TABLE

	fast scan (286 MHz)		slow scan (95.3 MHz)	
typical examples	rolling sh.	global sh.	rolling sh.	global sh.
2560 x 2160	100 fps	50 fps	33.6 fps	16.8 fps
1920 x 1080	201 fps	100 fps	67 fps	33.3 fps
1600 x 1200	181 fps	90 fps	60 fps	30 fps
1280 x 1024	212 fps	105 fps	70 fps	35 fps
640 x 480	450 fps	222 fps	150 fps	74 fps
320 x 240	893 fps	435 fps	297 fps	145 fps

DYNAMIC PROCESSES

Natural processes such as the fast movement of trypanosomes, which are shown as a sequence above, could only be investigated by a sCMOS camera such as the pco.edge. Using the camera, it is now possible to investigate living samples beyond steady state conditions to investigate dynamics even in low light conditions. In addition, the pco.edge sCMOS camera's high frame rate efficiently reduces recording times in applications such as spinning disk confocal microscopy, super resolution microscopy, structured illumination microscopy, as well as light sheet microscopy.

TRIGGER

SOFTWARE TRIGGER

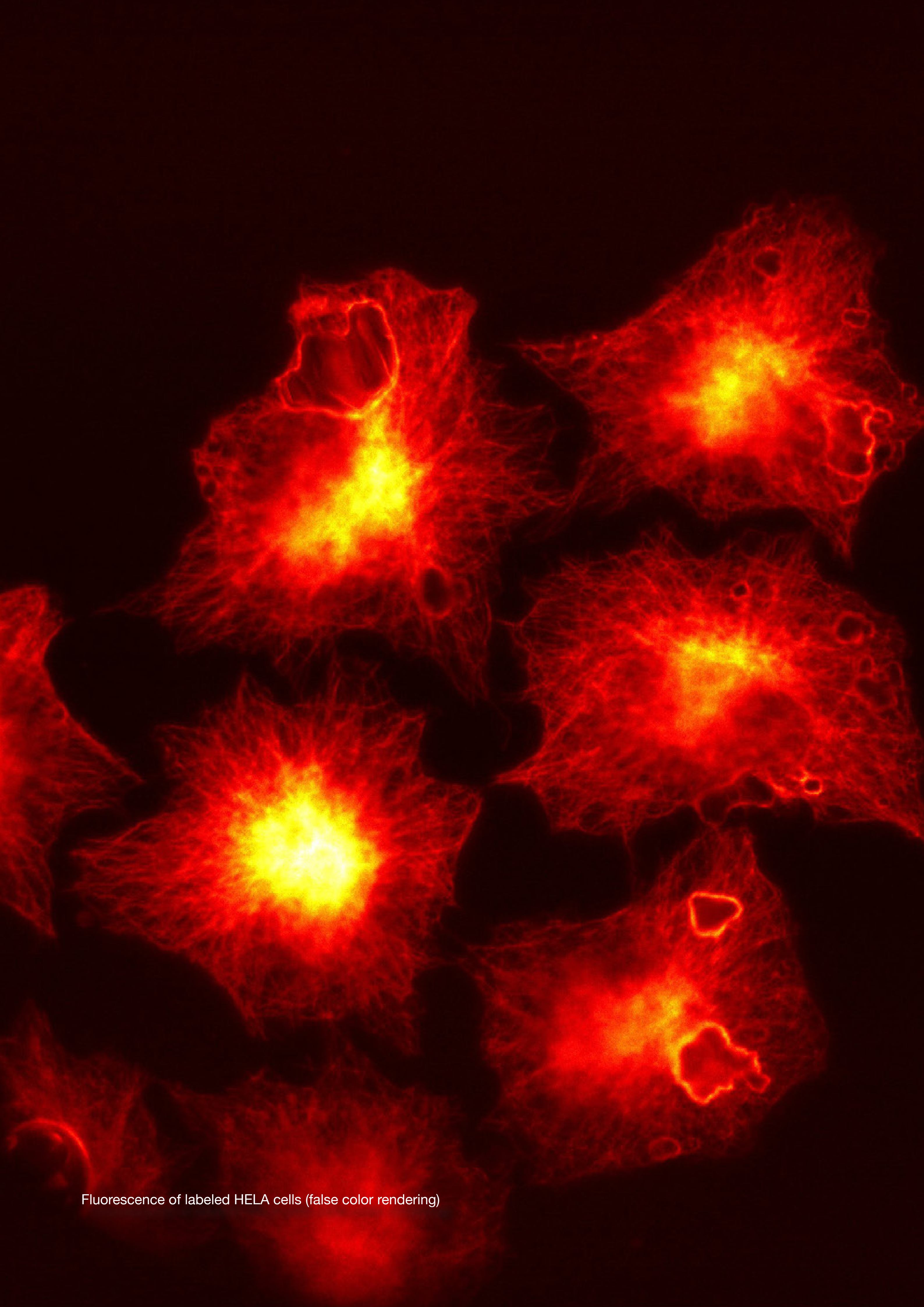
The pco.edge sCMOS camera can be fully triggered using software that records single images, as well as sequences in video mode. The video mode can also be limited to a defined number of images, called "burst" mode, and further, it can be started and stopped using hardware signals.

SINGLE IMAGE TRIGGER

It is possible to synchronize or trigger single images with a trigger signal or light source to facilitate the recording of an image sequence. In addition, even the exposure time per image can be controlled by an external hardware signal.

TRIGGER OUTPUT

All recording modes and status information are available as hardware signals at the camera outputs.

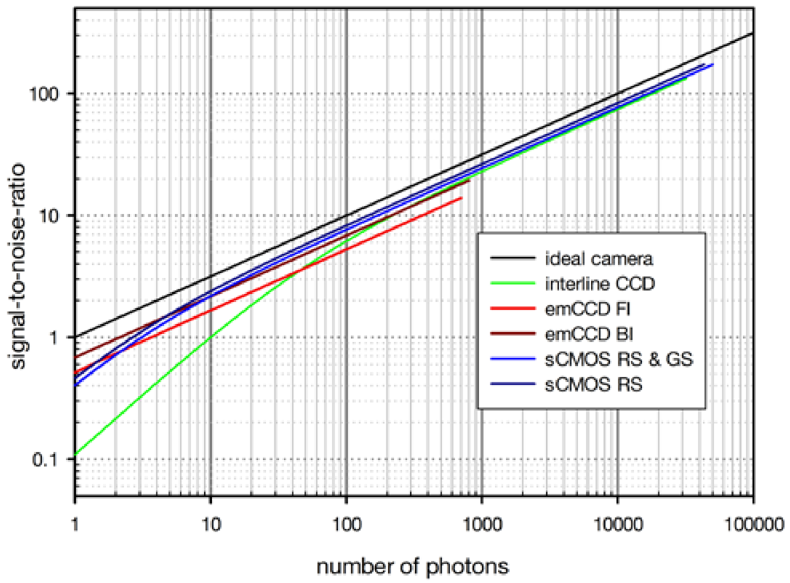


Fluorescence of labeled HELA cells (false color rendering)

SIGNAL-TO-NOISE-RATIO (SNR)

$$SNR = \frac{QE \times photons}{\sqrt{\left[enf^2 \times \left((QE \times photons) + dcn + cln^2\right)\right] + \left(\frac{rdn^2}{gain^2}\right)}}$$

The signal-to-noise-ratio equation with different parameters assuming a linear camera model, the variables are explained in the text on the opposite page.



The signal-to-noise-ratio curves of cameras with different scientific image sensors in relation to the number of photons as input signal for the cameras.
The progression of the curves demonstrates, that latest above 5 - 7 photons the sCMOS image sensor outperforms the competitive image sensors.

A single image of fluorescence labeled protein networks in water drops in an oil phase, which moved fast. One pixel corresponds to 0.1625 µm in reality.
Courtesy of Prof. Dr. Sarah Köster, Institute for X-Ray Physics, Georg-August-University, Göttingen, Germany

SCIENTIFIC IMAGE SENSORS

In order to compare the performance of scientific image sensors, it is useful to examine the technical term signal-to-noise-ratio (SNR). Generally, it can be assumed that a linear camera model is valid. This model shows that double the light will cause double the gray value in the image. The SNR expresses relation of the useful signal to the noise. This noise can be added to the signal by the image sensor, the camera electronics, and the signal itself. A good SNR is prerequisite for good image quality.

COMPARISON TABLE

	ideal camera	interline CCD	emCCD FI	emCCD BI	sCMOS RS & GS	sCMOS RS
quantum efficiency (**QE**)	1.0	0.55	0.55	0.93	0.6	0.7
readout noise (**rdn**) [e^-]	0	5	20	60	1.1	1.1
multiplication gain (**gain**)	1	1	100	1000	1	1
clock noise (**cln**)	0	0.05	0.05	0.05	0	0
dark current (**dcn**) [e^-]	0	0.001	0.001	0.001	0.63	0.63
excess noise factor (**enf**)	1	1	1.41	1.41	1	1
image sensor temperature [°C]	-	- 12	- 50	- 50	+ 5	+ 5

SNR EQUATION

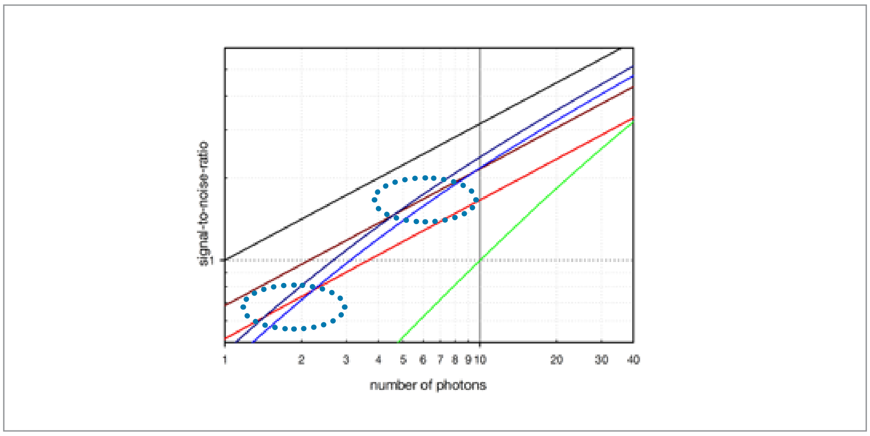
The formula on the opposite page describes all the parameters that are required to compare scientific image sensors. The signal is given by the product of number of photons and the quantum efficiency, which describes how many charge carriers are generated by a photon. The independent noise contributions are allowed to be added as noise power, which is the reason why the square root of the sum of the noise power is taken.

The noise contributions are: the sum of the signal itself (QE x photons), the dark current (dcn), and a clock induced noise (cln^2) multiplied with the excess noise factor (enf^2) coming from the multiplication process of emCCD image sensors, plus the ratio of the readout noise (rdn^2) divided by the multiplication gain ($gain^2$) coming from emCCD image sensors. For the value of the dark current an exposure time of 100 ms is assumed. The positive effect of the multiplication gain of emCCD image sensors is traded for an effective dynamic reduction and an additional noise parameter, the excess noise factor (enf^2). For comparison in the table as well as in the graphs there is also an ideal camera assumed. This camera has a 100 % quantum efficiency, no image sensor or camera noise - only photon noise and no gain. This ideal camera defines (in the SNR graphs on the opposite page and on this page) the scientific image sensor's upper performance limit, the photon's SNR and the photon noise. The various curves represent the SNR behavior of the different scientific image sensors, which are shown in the table. The end of each curve is determined by the effective fullwell capacity of each image sensor.

The green curve represents an example of a good interline transfer CCD. The curve shows that above 40 photons, it has a better SNR than the front illuminated emCCD (bright red curve). There are two emCCD curves, a front illuminated emCCD with 55 % QE (bright red curve) and a back illuminated emCCD with 93 % QE (dark red curve). There are two different sCMOS curves for two front illuminated sCMOS image sensors, one with 60 % QE (bright blue curve) featuring both Rolling and Global Shutter (5T architecture) and a pure Rolling Shutter (4T architecture) version with 70 % QE (dark blue curve).

red curve) and a back illuminated emCCD with 93 % QE (dark red curve). There are two different sCMOS curves for two front illuminated sCMOS image sensors, one with 60 % QE (bright blue curve) featuring both Rolling and Global Shutter (5T architecture) and a pure Rolling Shutter (4T architecture) version with 70 % QE (dark blue curve).

The graph below highlights an extract of the larger graph on the opposite page, zooming in on the 1 - 40 photon range, so that the various intersection points of the SNR curves are seen more clearly. One can see that the sCMOS image sensor's SNR curve starting at 2 photons better than the front illuminated emCCD image sensor, and starting from 5 - 7 photons better than the back illuminated emCCD image sensor. Above these light levels, sCMOS image sensors deliver superior image quality.



ROLLING / GLOBAL SHUTTER

As opposed to conventional CMOS image sensors the sCMOS image sensor in the pco.edge camera allows for both operational modes. This enables the excellent low noise performance offered in rolling shutter mode and the outstanding short exposure values provided in global shutter mode.

ROLLING SHUTTER

The rolling shutter as it is shown in the upper figure on the opposite page, is very similar to the former slotted shutter in single lens reflex (SLR) cameras. The sCMOS image sensor features a "row" operation. The exposure time of each row starts with the corresponding reset of the row. Then after a predefined time, exposure is stopped. The light induced accumulated charge carriers of the pixels in a row are recorded into memory in a low noise fashion. This results in the total image appearing in memory corresponding to the row readout.

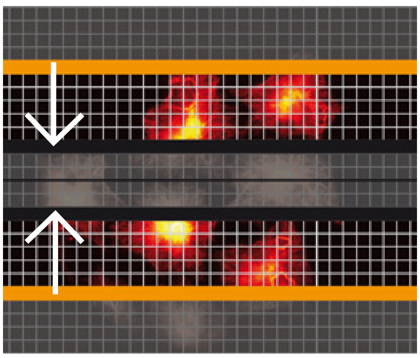
Obviously, if during exposure and readout, parts of the viewed image are moving horizontally, it would result in image distortion. This is why the global shutter mode may be a prerequisite for some applications such as particle image velocimetry, where the exact position of scattering particles is compared between two consecutive images. However, as most dynamic events can be captured in 1 ms, as is evident with the use of SLR cameras set at 1/1000 exposure, maximum readout time for the sCMOS image sensor of approximately 10 ms is sufficient. The 10 ms is also faster than the image shift process of most frame transfer emCCD image sensors previously used for low light applications. If this does not influence image recording and processing, then rolling shutter mode will not affect it either.

GLOBAL SHUTTER

The global shutter exposure process is shown in the lower part of the opposite page. First, all the charge collecting diffusion nodes in all pixels are globally reset. From there these dark image values are non-destructively read out into memory as reset dark image. Now the photo diodes of all pixels are globally reset and the exposure of the image starts. Then the exposure is stopped by global charge transfer to the diffusion nodes, where they are added to the dark values. Afterwards, the exposure image is read out to the memory, where the former reset dark image is subtracted to perform an external correlated double sampling, which reduces the inherent kTC-noise of the image[1]. Since two images have to be readout to receive one resulting image, the sCMOS image sensor's global shutter mode has only half of the frame rate of the rolling shutter mode.

HIGH SPEED

The high frame rate of the sCMOS image sensor is achieved by stitching two halves of the same chip together. In the pco.edge camera both halves are read out simultaneously from the outside to the inside, as shown in the photo below. Therefore, to maintain the fast readout speed, the region-of-interest (ROI) in the pco.edge camera must be "center symmetrical" selected. If competitors offer a free selection of ROI, it is done in the memory and does not inrecase the frame rate.



SCMOS & GENERATION X ?

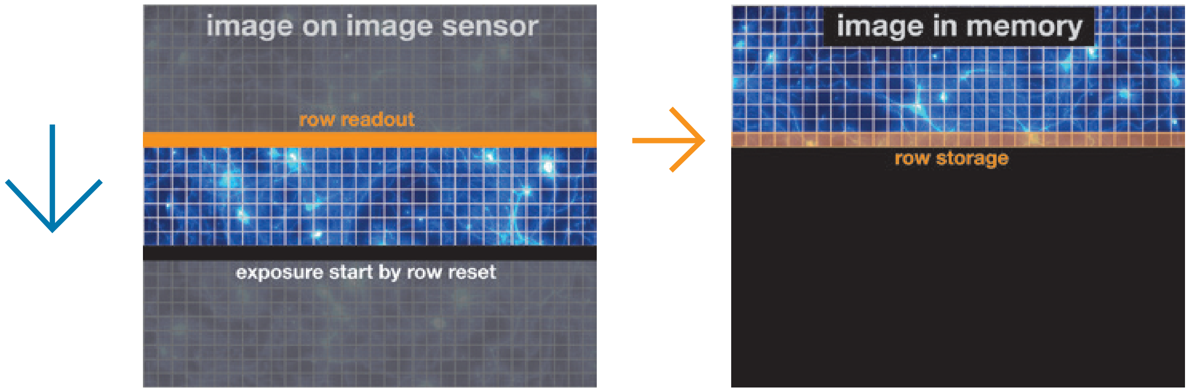
The expression Scientific CMOS or sCMOS, as it is now known, was selected by the three companies that developed the technology: Fairchild Imaging, Andor Technology and PCO AG. The term was chosen because it differentiated the new sCMOS image sensor from the established perception of CMOS image sensors. Previously, the common impression of CMOS image sensors was that they were useful for high frame rates, but they always had high readout noise and moderate dynamic. The new structure of the sCMOS image sensor enabled an outstanding combination of performance parameters, which had not previously been achieved.

Although there is no difference in the manufacturing process or the materials used in creating this new image sensor, a new term: *scientific CMOS (sCMOS)* was selected.

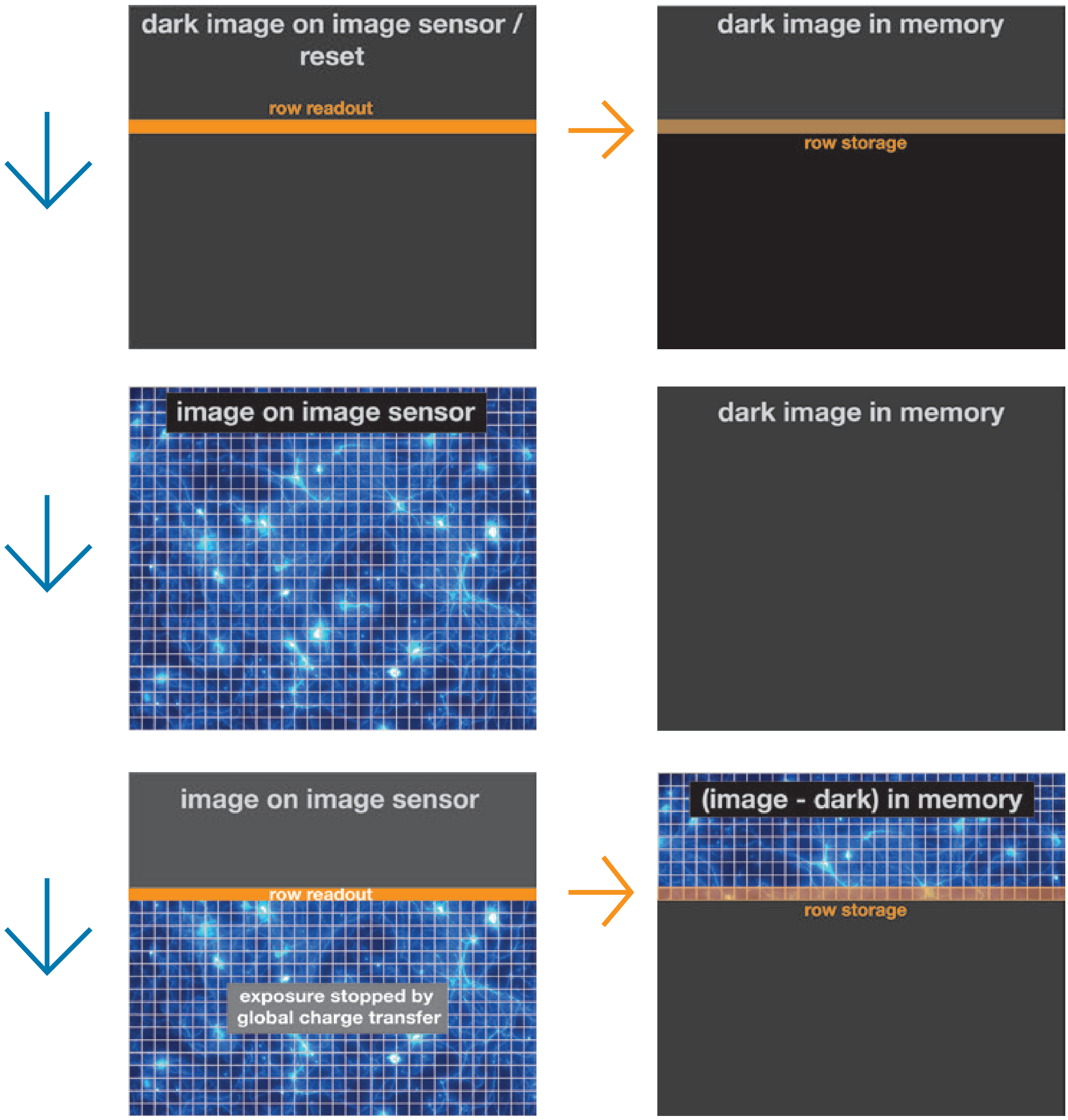
During the development process of the sCMOS image sensor, several different architectures were investigated. One such architecture was a pure rolling shutter version, which offered slightly better quantum efficiency, based on one fewer transistor and fewer layers. But the baseline was still the original sCMOS structure and does not reflect a new or next generation sCMOS image sensor.

[1] The kTC-noise of an image sensor usually is reduced by correlated double-sampling (CDR), where the dark reset noise value is stored and after exposure subtracted from the measured value. In rolling shutter mode this is done automatically on the chip per row, while in global shutter mode it has to be done after reading out.

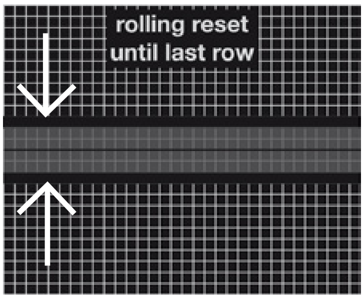
ROLLING SHUTTER

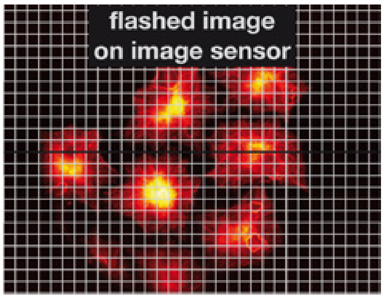


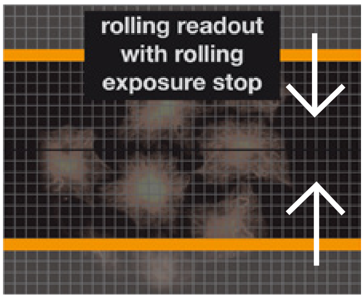
GLOBAL SHUTTER



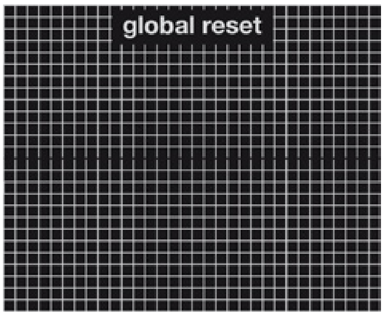
ROLLING SHUTTER

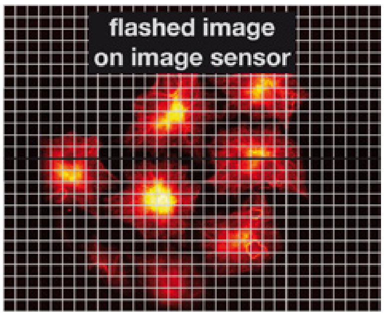


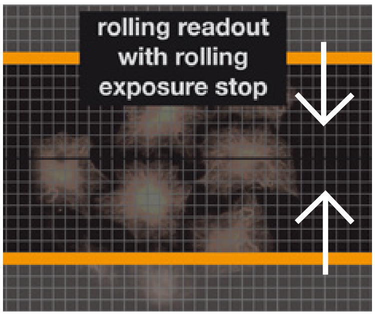




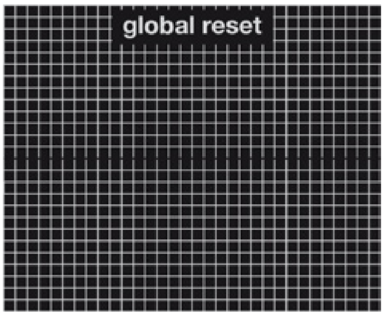
GLOBAL RESET - ROLLING SHUTTER

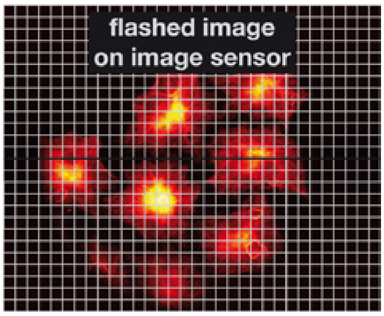


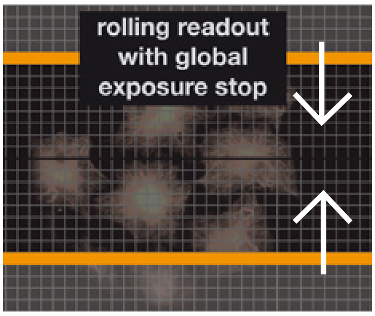




GLOBAL SHUTTER







FLASH ILLUMINATION

Three different operational modes are available when the pco.edge sCMOS camera is used with flash illumination. They have different effects on the trigger relation between camera and flash light and the time delays attributed to them.

ROLLING SHUTTER

When rolling shutter mode is used, the flash light must delay until the last row is reset (see upper images on the opposite page). Then the flash is started and the flashed image is detected on the image sensor. After completion of the flash illumination and in total darkness, the image is read out in rolling shutter mode, where the row readout stops the exposure. The flash controls the actual exposure time, but every row experiences the same total exposure time. This means that every row accumulates the same amount of dark current. This mode is used in the case where the camera is used as the master trigger source and the flash illumination follows the camera trigger.

GLOBAL RESET - ROLLING READOUT

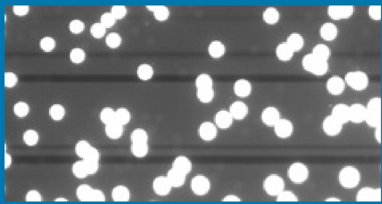
Global reset mode is a special mode for the unique case where camera action is triggered by flash illumination. Initially, the image sensor is reset globally (see middle images opposite page), then the flash illumination takes place and the resulting image is detected on the image sensor. After completion of the flash illumination and in total darkness, this resulting image is read out in rolling shutter mode. The difference between “Global Reset - Rolling Readout” and “Rolling Shutter“ mode is that now the last row read out has the longest time to accumulate dark current. Dark current contribution will be the sum of exposure time + readout time, which in most imaging applications can be ignored because of short exposure times and the small dark currents. However, if dark current is to be considered, it can be corrected because it is a linear increase and the parameters are known. This special mode provides less readout noise and dark current noise as compared to “Global Shutter” mode.

GLOBAL SHUTTER

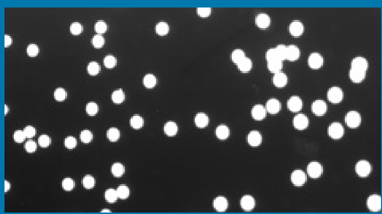
In global shutter mode, the image sensor is globally reset (see lower images on the opposite page), then the flash is started and the flashed image is detected on the image sensor. After the flash, the exposure is globally stopped and the image is read out row by row. This is the preferred operational mode for particle image velocimetry (PIV). The only disadvantage of global shutter mode is slightly increased readout noise and a lower frame rate.

ILLUMINATION CAN GO WRONG

Similar to other image sensors, the sCMOS sensor has additional columns and rows that have no optical functionality and those, which are shielded, and should behave like real pixels without being influenced by light. This would enable their readout to be used in the camera for correction and control purposes. For example, the readout from these shielded pixels can be used to maintain a constant offset, independent of temperature variations (referred to as “dynamic baseline clamping” by some manufacturers).
However, experience has proven that shielding those pixels is not sufficient for scientific referencing. The pixels closer to the shield boundary can even catch up more light when the sensor is illuminated in that region, because the aluminium or paint layer on top of the sensor structure allows for scattered light below the shield. If shielded pixels are used for referencing purposes, then only in these rows the offset is adjusted and dark horizontal stripes appear in the image. The quality of shielding and usefulness of pear in the image. The quality of shielding and usefulness of reference rows and columns may vary from sensor architecture to sensor architecture. Therefore, the image sensor’s behavior must be thoroughly tested in every case.
In the pco.edge sCMOS camera a different and more efficient method is used in order to provide a stable and constant offset.



Extract at the boundary of a competitor’s sCMOS camera (@ - 40 °C). The image of fluorescent test beads illustrates the issue of reference pixels when illumination falls onto the boundary. The dark bands from the changed offset are clearly visible.



A similar image of the same test beads as above using the pco.edge (@ + 5 °C) shows that the offset control of the pco.edge performs efficiently.

COOLING

Image sensor cooling is a well established method to improve the performance of cameras used in scientific applications. This improvement is done for two main reasons, achieving temperature control and maintaining a low temperature.

TEMPERATURE CONTROL

An image sensor's temperature control is important in order to create a stable temperature environment for the image sensor. This allows to achieve a stable offset value (formerly also known as "black shoulder"). In high-quality camera systems, dark images (images with no light) are not zero, but always have a small offset. This is purposely done to have the complete readout noise in the image for evaluation, and to offer stable and detectable dynamics, since the lower end of the image's signal contrast is always detectable. Without this temperature control, continuous recording would show a temperature increase, depending on the environmental temperature, and the offset would change accordingly. Therefore, the image sensor's temperature control keeps offset and dynamics stable. For this purpose, the absolute value of the temperature is irrelevant, but the temperature must be kept stable. The pco.edge sCMOS camera is thermoelectrically (TE) controlled at + 5 °C for this reason.

LOW TEMPERATURE

The second reason for cooling is its influence on a temperature-induced unwanted signal called dark current. Dark current contributes to the readout noise in response to temperature and exposure or shutter time. It can be reduced by low temperature or a short exposure time. In applications with large sensors and long exposure times, such as in astronomy, these image sensors are cooled down to very low temperatures. In case of the sCMOS image sensor, cooling helps to reduce the noise contribution of the dark current in exposure times above a couple of seconds. However, for exposure times below one second, it can be neglected.

Low temperature also has an influence on locally fixed "hot pixels". These are pixels that have much higher offset values because of crystal lattice defects, or are simply bright and don't react to light any longer. The total quantity of these "hot pixels" is temperature dependent, with the consequence, that the lower the temperature, the fewer "hot pixels" occur. In every high performance camera the "hot pixels", considered defect pixels, are calibrated, which means that they are detected, their positions are stored, and the corresponding pixel values are replaced by the neighborhood average value. If this neighborhood operation feature is not wanted, it can be switched off via camera software. Most high-quality cameras include "hot pixel" readout lists. Independent of the absolute temperature in a scientific camera, the "hot pixels" are not visible, because they are calibrated at the corresponding temperature, which is the case in the pco.edge camera.

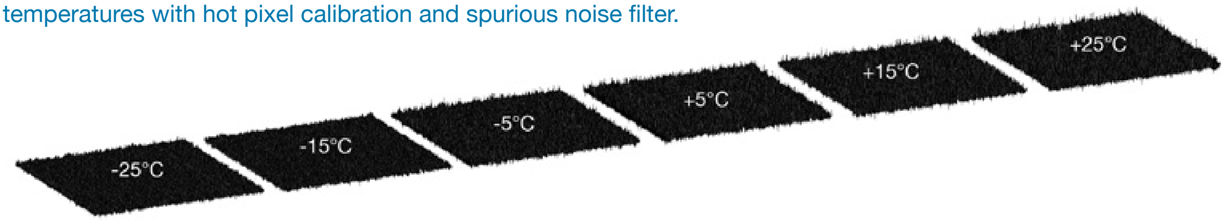
NO INFLUENCE OF COOLING

CMOS and sCMOS image sensors have non-permanent, localized pixels, with significantly increased offset, which makes them brighter than the average pixel. Since they are not always brighter, in an image sequence, it looks like they are blinking. That is why they are commonly called blinkers. They are impurities in the semiconductor crystal lattice and the visual impression is similar, like the spurious charges in emCCD image sensors, which are also non-constant bright pixels in dark images. Unfortunately, the number of these noise pixels doesn't have a dependence on the temperature, so cooling doesn't help in this situation. In comparison to emCCD, these blinkers are locally fixed and can be removed by sophisticated software algorithms in the cameras. In every high performance camera, including the pco.edge, this feature can be switched on and off using software.

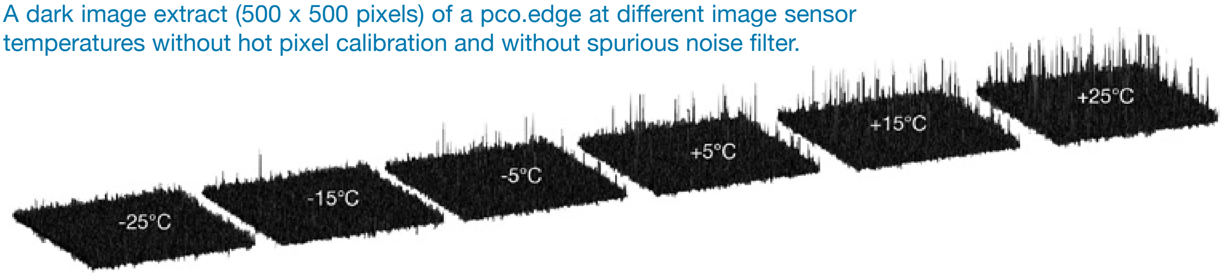
COOLING CAN BE BAD

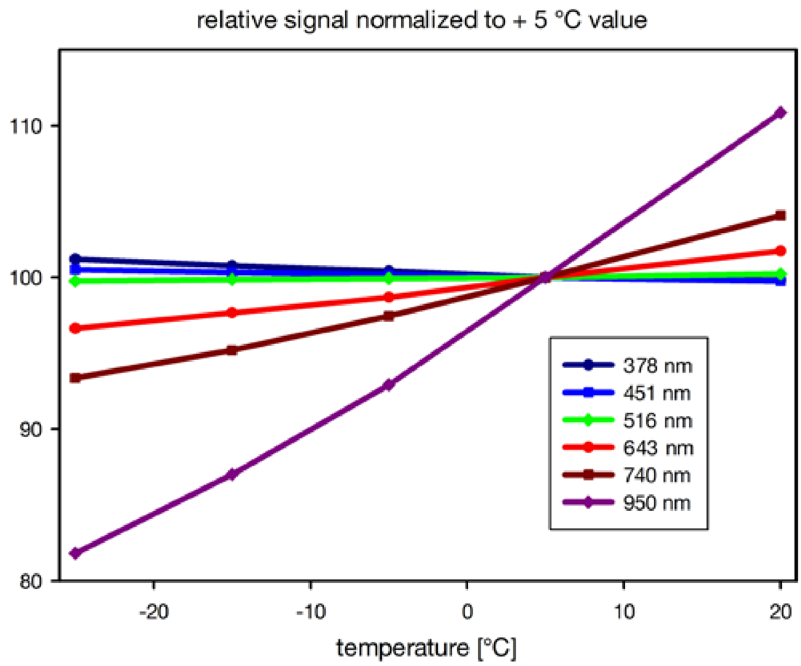
Cooling reduces the mobility of charge carriers in the image sensor's semiconductor material. This also influences the effective quantum efficiency. The lower graph on the opposite page shows the sCMOS image sensor's relative quantum efficiency measurement at different spectral wavelengths, dependent on the temperature. Clearly, the NIR sensitivity of the the sCMOS image sensor is reduced by cooling. For example, if the sCMOS image sensor should be used for electroluminescence measurements at a wavelength of λ = 1000 nm, then cooling would be detrimental.

A dark image extract (500 x 500 pixels) of a pco.edge at different image sensor temperatures with hot pixel calibration and spurious noise filter.



A dark image extract (500 x 500 pixels) of a pco.edge at different image sensor temperatures without hot pixel calibration and without spurious noise filter.





A measurement of the temperature dependence of the signal at different wavelengths. The signals were related to the value measured at +5 °C, therefore it corresponds to a relative QE measurement.

Autofluorescence of a lily of the valley section (false color rendering)

IMAGE DATA FLOW

The sCMOS image sensors provide an extremely high frame rate compared to other scientific image sensors. The high frame rate, along with the high dynamic, creates a large amount of data that must be handled and stored. The maximum data rate of the sCMOS image sensor is given by:

*[2560 * 2160 pixels (in 1 frame) * 2 Byte (= 16 bit dynamic)] * 100 frames/s = 1.1 GB/s*

To handle this considerable amount of data there are mainly two options available.

1 RECORDING TO COMPUTER

The pco.edge camera uses this option. For this purpose, the interface must be capable of transmitting data at the required speed. The table gives an overview of the theoretical and practical bandwidth of actual data interfaces that are used for the image data transmission.

One can see that interfaces such as GigE, USB 3.0 and Camera Link are not fast enough to transmit this data, which is delivered by the largest sCMOS image sensor. Nevertheless, there is a sophisticated solution that uses the Camera Link interface, which is integrated into the pco.edge camera. It is a fact of nature that light, itself, has its own noise component called “photon or shot noise”, which increases with light signal. In this approach, no compression is made in small signals, while for large signals a suitable compression is applied. Since the introduced compression error is always smaller than the photon noise induced error, it is not seen and a so-called “visual lossless” compression has been performed. It can be shown that this is possible without any significant loss of information[1]. Therefore, the calculation for the pco.edge camera at full speed and full frame rate has to be rewritten:

*[2560 * 2160 pixels (in 1 frame) * 1.5 Byte (= 12 bit dynamic)] * 100 frames/s = 0.829 GB/s*

The Camera Link interface can transmit this information in real-time. In the future, recently-introduced machine vision interfaces including CoaXPress and Camera Link HS are capable of transmitting sCMOS image data without any compression. A network type interface, 10 GigE, is similar with respect to hardware to Camera Link HS, but incorporates all of the known GigE advantages and disadvantages. Here, the usual protocols are not favorable for image data transmission, and any network traffic can dramatically reduce available transmission speed. The real-time data transmission into the computer allows for a variety of applications, since it is free from camera memory limitations. Image data can be stored directly in the computer’s random access memory (RAM), up to more than 64 Gigabyte. With an appropriate RAID system, the data can be stored directly to hard disks and there is no delay involved.

TABLE

interface	theoretical bandwidth [GB/s]	practical bandwidth [GB/s]	
Camera Link	0.85	0.85	pco.edge
USB 3.0	0.4	0.38	
CoaXPress	0.62	0.6	
Camera Link HS	1.25	1.2	
GigE	0.12	0.1	
10GigE	1.25	1.2	

2 RECORDING IN THE CAMERA

For high-speed imaging applications, where data transfer rates are in the range of several Gigabyte/s, it is accepted that the primary image memory (camRAM) must be located in the camera. Two examples of such high-speed cameras are the pco.dimax with 36 GB of camRAM and the pco.dimax HD with 18 GB of camRAM memory. This allows for the fast recording, but just up to the integrated memory limit. Before a second sequence can be recorded, one must endure the wait time until data is downloaded to computer storage. Therefore, this option can only be used for recording short sequences with enough time between each event to download the image data.

If data streaming is possible (option 1), it is the favorable and more flexible solution.

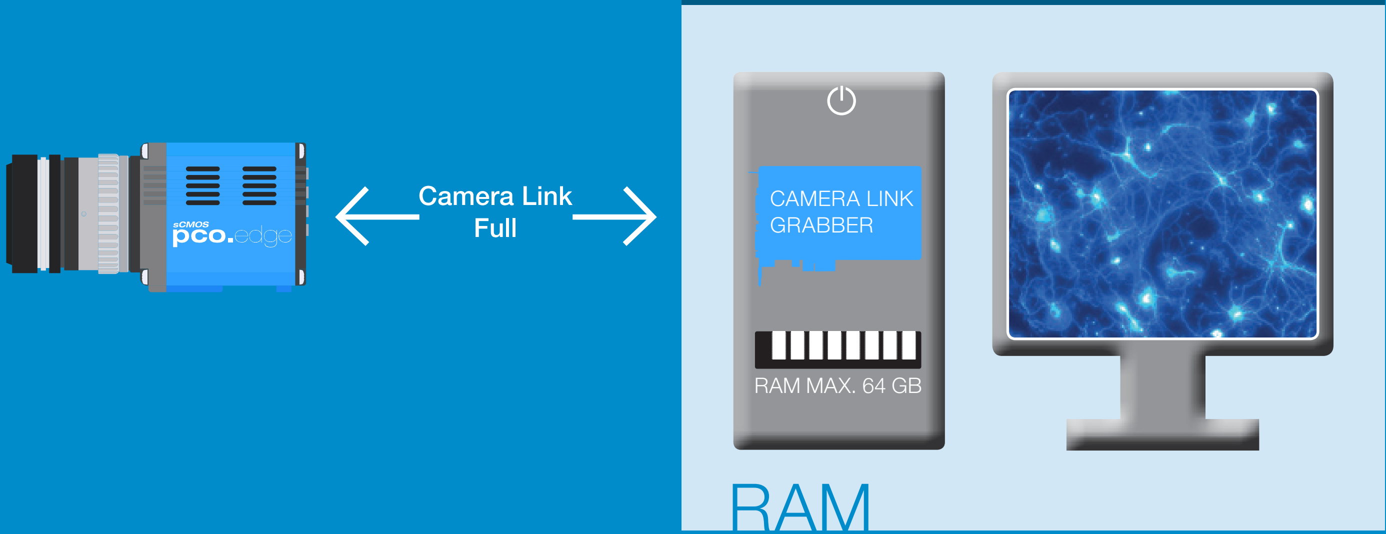
MEMORY STRUCTURE / ORGANIZATION

As the memory is software-controlled in both options, it does not matter how the data are stored. The memory can be organized for ring buffer or FIFO recording, or for a specified number of images like a “burst” mode. The pco.edge camera enables all of these possibilities with the integrated dynamic link libraries and proprietary pco.camware application software. This allows the customer to select the memory structure and organization that is optimized for the application at hand.

[1] Bernd Jähne, Digitale Bildverarbeitung und Bildgewinnung, 7th edition, Springer Vieweg, 2012, ISBN 978-3-642-04951-4, chapter 7.2.4

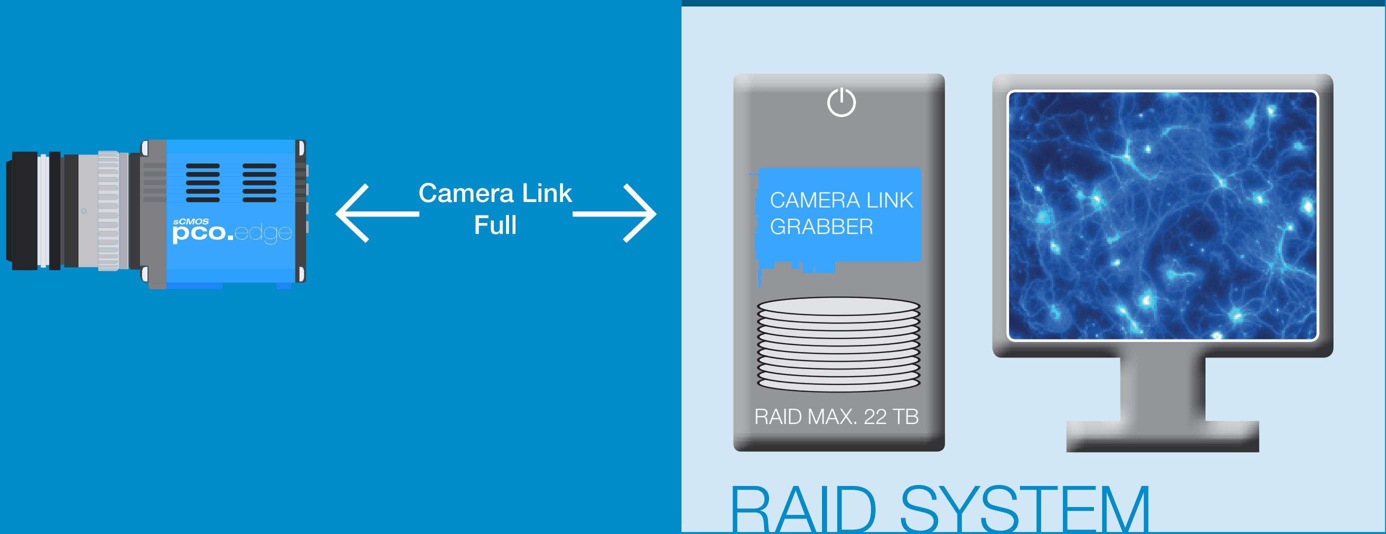
RECORDING IN REALTIME TO COMPUTER

RAM RECORDING

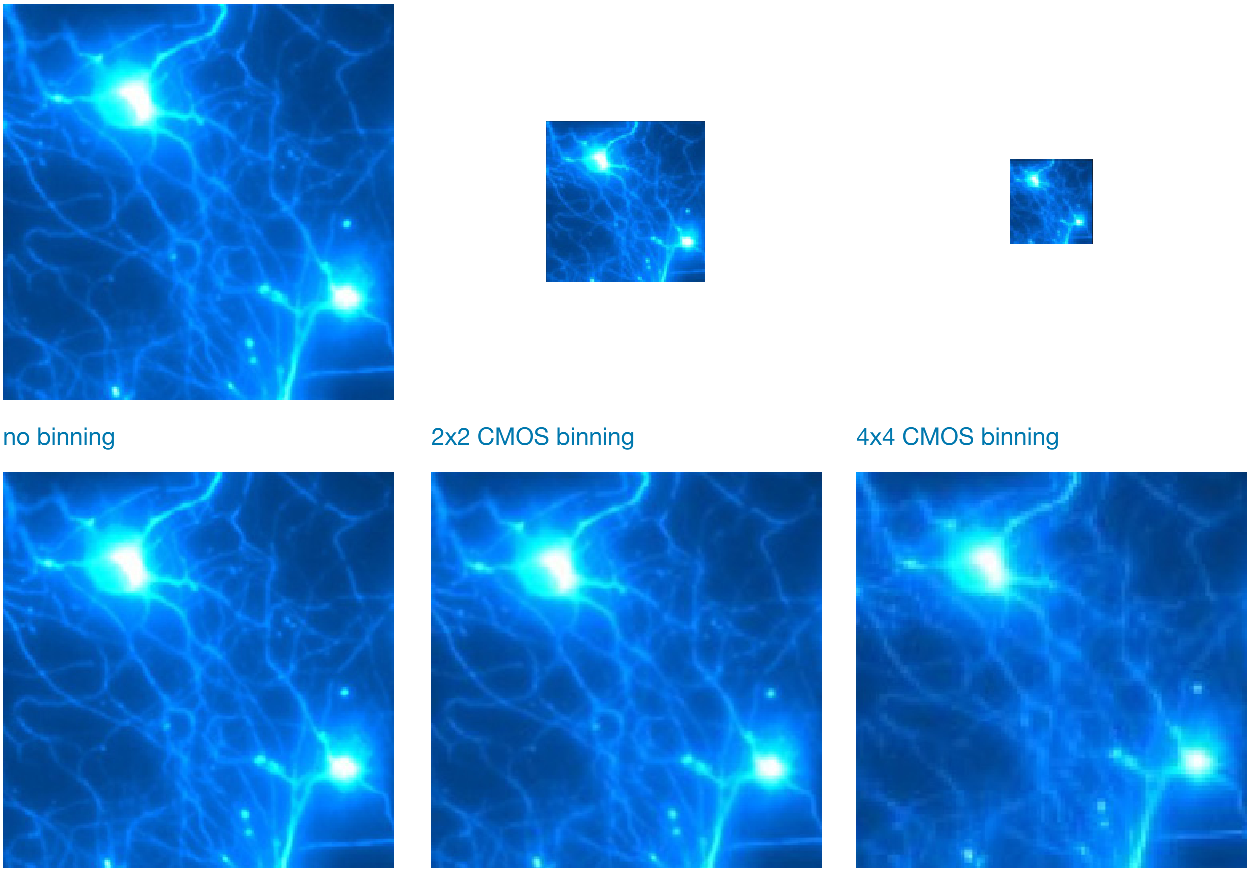


The pco.edge image data can be directly recorded to the computer RAM up to the available RAM size, even larger than 64Gigabyte. Then the data will have to be stored to a hard disk. This is independent of the memory structure, it can be ringbuffer, FIFO or bursts.

HD RECORDING



The pco.edge image data can be directly recorded to a computer with a RAID system of hard disks up to the Terrabyte size. This is independent of the intended storage structure, it can be continuous storage or burst storage.



The series of processed images demonstrates the effect of binning by averaging. The upper row shows the real loss in resolution by 2 x 2 and 4 x 4 binning. In the lower row, the same upper row images are resized to the original "no binning" image size, clearly illustrating the resolution loss.

Neuronal network marked with a fluorophor (false color rendering)

BINNING

Binning describes the summation of single pixels to form larger pixels, thereby improving the signal-to-noise ratio (SNR).

BINNING IN CCD IMAGE SENSORS

The term binning comes from scientific CCD image sensors. The prominent feature of charge-coupled-devices (CCD) is the lossless transport or shifting of charge packages until an amplifier circuit converts them into a voltage at the output, where the main readout noise contribution occurs.

If charge packages from two or more pixels are added before they are read out (past the output amplifier) because of low light signals, this process is called binning. Since the signal is increased before it is read out, and the image sensor's readout characteristics remain unchanged, binning improves the SNR, and the image sensor's resolution is reduced. The lossless transport feature of CCD image sensors makes binning possible.

BINNING IN CMOS IMAGE SENSORS

In general, there is no binning possible in CMOS image sensors because there are voltages processed instead of charges transported. In each pixel, the light generated charges are converted into voltages with the readout noise contribution of these amplifiers. Therefore, as opposed to CCD image sensors, if these voltages were combined, their readout noise would also be combined, which would not have the same positive effect on the SNR. Nevertheless such a summation or even an averaging would be beneficial for the SNR, but with a smaller impact compared to CCD image sensors. Since such a "CMOS binning" cannot be done within the image sensor, it either has to be done in the camera or it has to be done in the computer.

There are two options for "CMOS binning":

"CMOS BINNING" – ACCUMULATION

Pixel values can be accumulated, causing an effective dynamic reduction or larger number formats, because the result might exceed the original format - two times maximum 8 bit values will result in a 9 bit value. This will not be a problem if 12 bit values are accumulated and transported as 16 bit images. However, in case of scientific CMOS, if 16 bit values are transmitted in 16 bit images, only 15 bit maximum values are allowed for this way of "CMOS binning". The SNR improvement is approximately the square root of the readout noise. Ultimately, a reduction of the transmitted image data is achieved.

"CMOS BINNING" - AVERAGING

Pixel values can be averaged, which improves SNR by the square root of the sum of the readout noise of the averaged pixels. This would keep the image data output format the same and would reduce the amount of image data that must be transmitted.

When this type of "CMOS binning" is processed in the camera, as it is done in the pco.edge camera, it is called "hardware binning". This should not be confused with real binning in CCD image sensors, because the "hardware" that processes this binning is not much different from the "hardware" in computer processing. Therefore, the term "hardware binning" may be misleading.

QUALITY

PCO takes pride in the manufacture of cameras that meet the highest possible quality standards. The company's cameras are reliable and built with the accuracy to satisfy the scientific demands in industrial, laboratory and military applications.

Since 2000, PCO has been serving on a Working Group at the European Machine Vision Association[1] (EMVA) to create a standard called EMVA 1288. The "Standard for Measurement and Presentation of Specifications for Machine Vision Sensors and Cameras" explains how to measure and characterize image sensors and camera systems. The EMVA1288 is accepted worldwide, since the corresponding American organization, the Automated Imaging Association (AIA), and the Japanese organization, Japan Industrial Imaging Association (JIIA) signed a contract with the EMVA to exchange and inherit the imaging standards. In this way, EMVA 1288 was expanded from a European standard to become an international standard.

While we use the EMVA1288 standard for our own quality control at PCO, typical serial cameras are always sent to an independent test lab, which verifies them following the EMVA 1288 standard. The results graphed on the opposite page contain data that was measured by a test laboratory (AEON[2]) and show an extract of the measurements. The first graph shows the linearity of the pco.edge sCMOS camera over the whole 16 bit range with the offset corrected mean signal in digital numbers (grey levels or counts) vs. the input signal in photons per pixel. The second graph shows the camera's variance over the whole range of input light levels as variance in digital numbers (squared) vs. offset corrected mean signal. The third graph shows the measured signal-to-noise values as SNR vs. the input signal in photons per pixel. Here, the natural limit, given by the photon noise, as shown as the black curve, is added as reference.

1288 EMVA Standard Compliant

The motivation for these efforts is to offer customers the highest quality camera systems in order that they can focus exclusively on their work – applications, scientific questions, experiments, measurements – and not worry about their camera.

LINEARITY

A perfectly linear camera can be efficiently used for quantitative measurements, since high linearity means that when the signal doubles, so does the camera output. Therefore, a direct relationship exists between the light from the imaged object and the digital output.

PHOTON-TRANSFER

Photon-transfer measurement and evaluation was first published by J. Janesick[3] in 1985 during a SPIE conference. It describes the relation between the image's temporal noise and the mean signal over the full signal range. It can be efficiently used to determine the overall system gain, which is the conversion factor between the light induced charge carriers, the electrons, and the digital values of the recorded image. Similar to the graph on the middle of the next page, minute influences such as merging the 11 bit values to create a 16 bit output (lower part of the curve) or some electrical crosstalk (middle part of the curve) can be easily detected. Measuring the photon transfer curve is a simple yet powerful method to characterize an image sensor or a camera system.

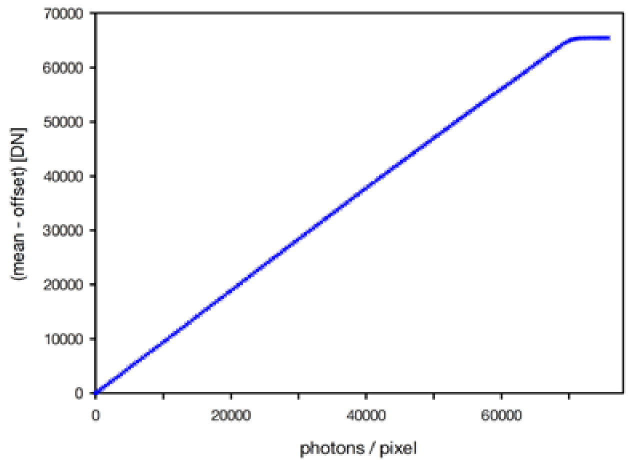
SIGNAL-TO-NOISE-RATIO

In the double-logarithmic-scaled graph (lower graph on opposite page) the SNR curve of a pco.edge sCMOS camera can be seen. It shows the readout noise dominating part at the beginning, the middle part, which is parallel to the "only" photon noise curve, the natural limit, which is the photon noise dominating part. At the end, when the photon noise gets clipped, meaning that the total photon noise cannot be measured because the image senor's saturation is approached, the SNR is increasing, until the image sensor becomes saturated. This graph gives a good overview of the camera's useful application range. Below SNR = 1, no imaging can be done, and the upper limit is given by the signal value where the measurements start to show non-linear behavior.

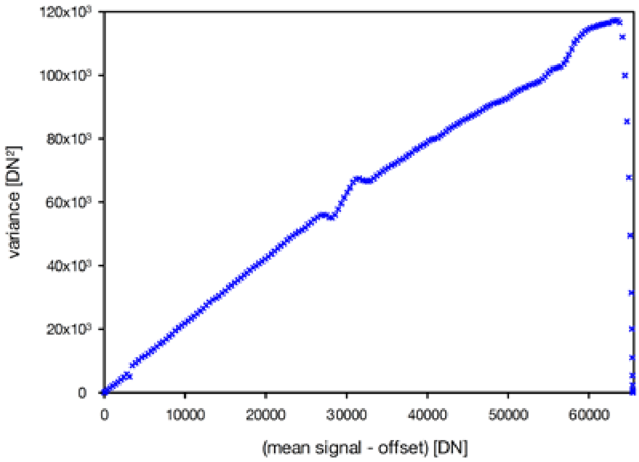
1 www.standard1288.org
2 Technical Report M0191, AEON Verlag & Studio GmbH & Co. KG, Hanau, Germany
3 Janesick, J. R. CCD characterization using the photon transfer technique. Solid State Imaging Arrays, vol. 570 of SPIE Proc., pp. 7-19, 1985

EMVA 1288 MEASUREMENTS

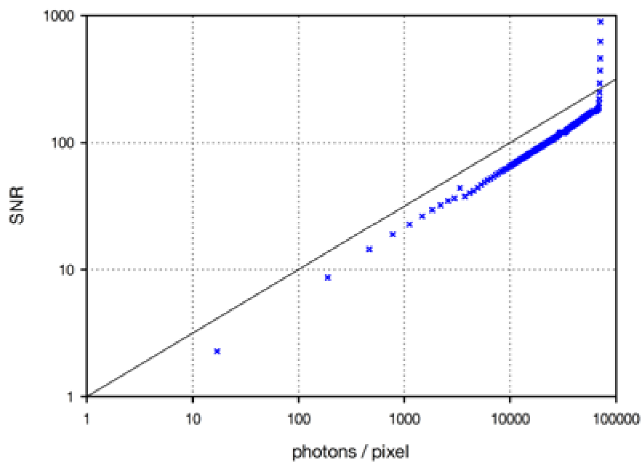
LINEARITY



PHOTON-TRANSFER



SIGNAL-TO-NOISE-RATIO



APPLICATION AREAS

WIDEFIELD MICROSCOPY, FLUORESCENCE MICROSCOPY

DIGITAL PATHOLOGY

PALM, STORM, GSDIM, DSTORM, SUPER RESOLUTION MICROSCOPY

LIGHT SHEET MICROSCOPY, SELECTIVE PLANE IMAGING MICROSCOPY (SPIM)

CALCIUM IMAGING

FRET, FRAP

3D STRUCTURED ILLUMINATION MICROSCOPY

HIGH SPEED BRIGHT FIELD RATIO IMAGING

HIGH THROUGHPUT SCREENING, HIGH CONTENT SCREENING, BIOCHIP READING

PIV

TIRF, TIRF MICROSCOPY / WAVEGUIDES

SPINNING DISK CONFOCAL MICROSCOPY

LIVE CELL MICROSCOPY

3D METROLOGY

TV / BROADCASTING

OPHTALMOLOGY

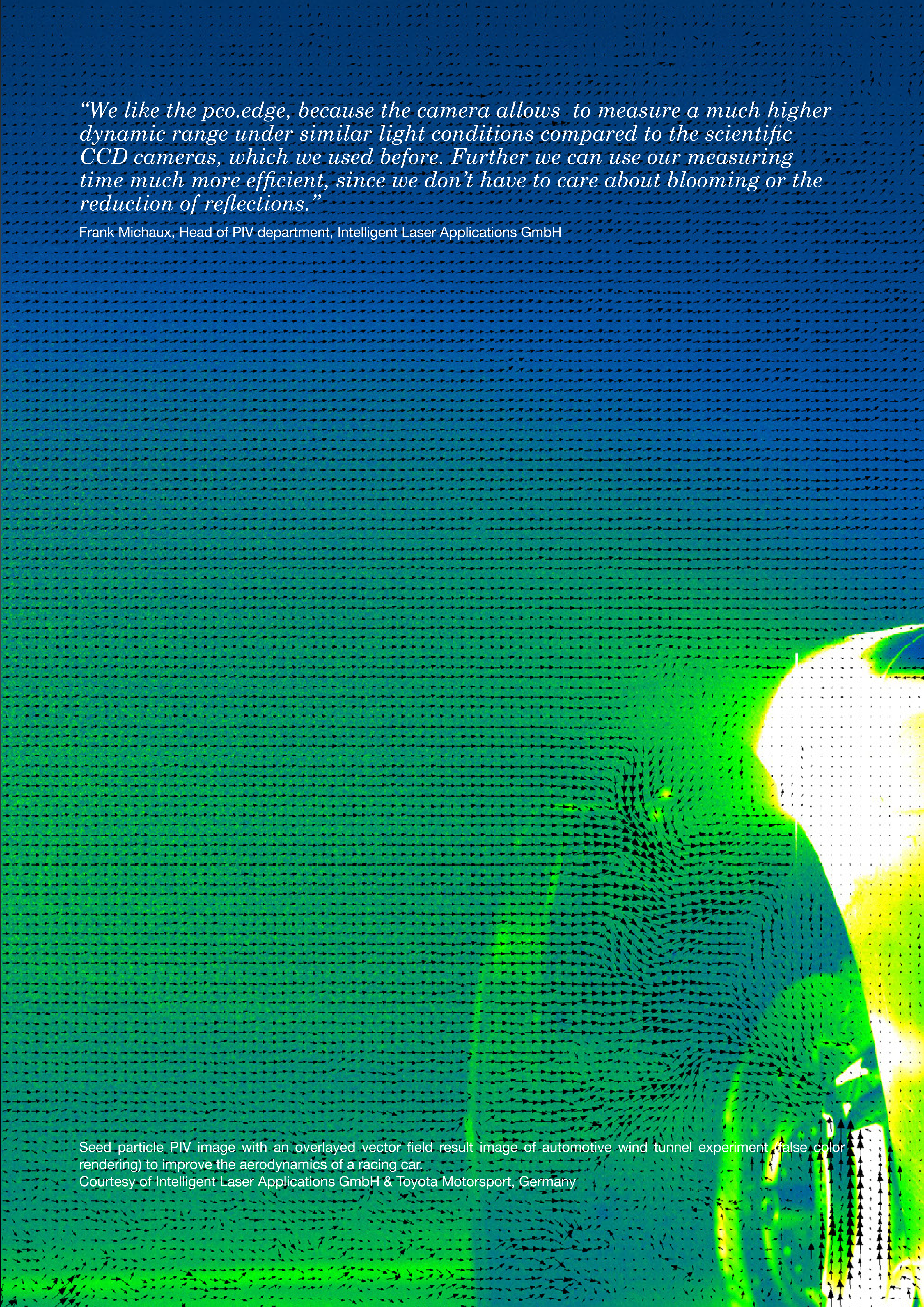
ELECTRO-PHYSIOLOGY

LUCKY ASTRONOMY

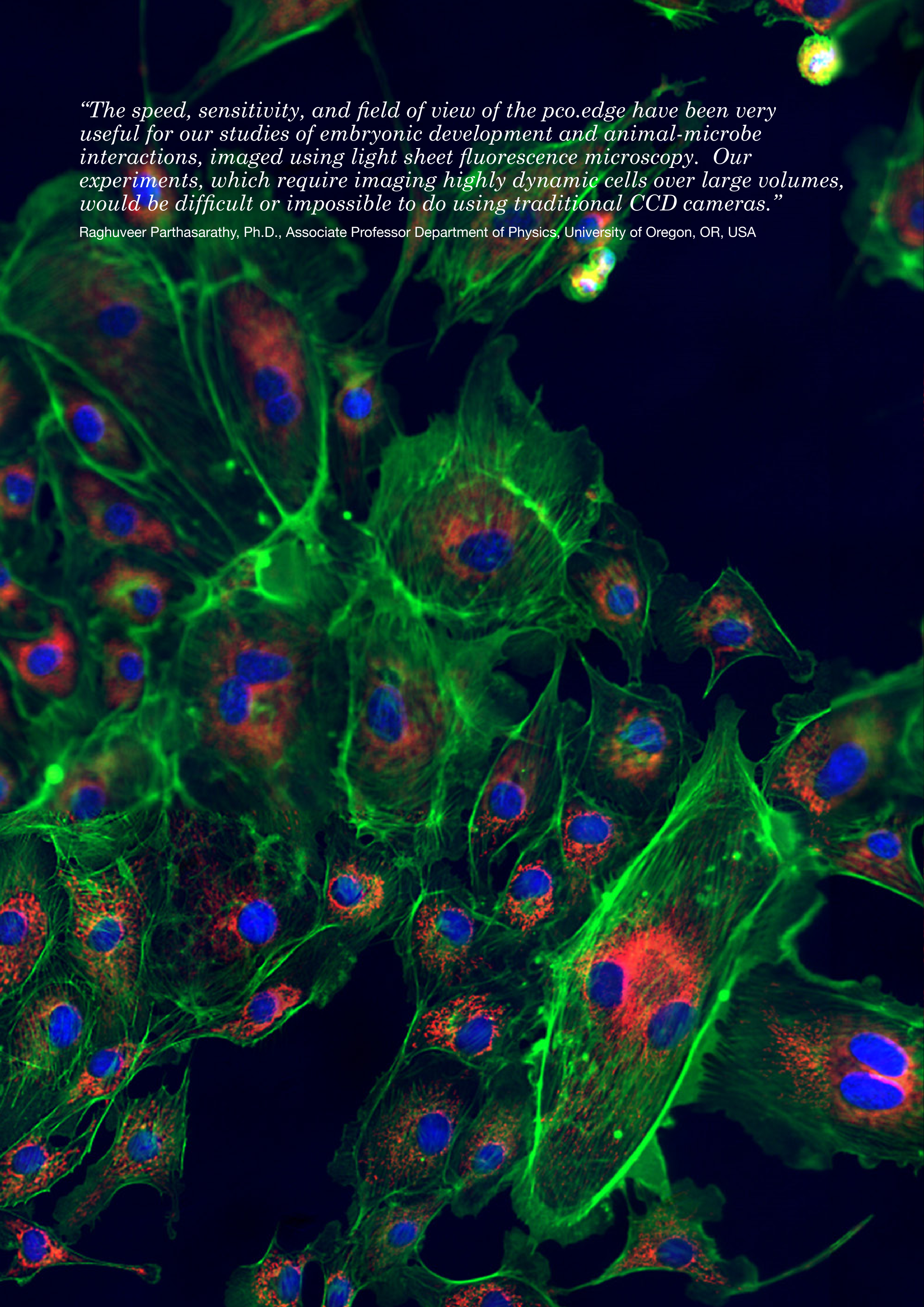
PHOTOVOLTAIC INSPECTION

“We like the pco.edge, because the camera allows to measure a much higher dynamic range under similar light conditions compared to the scientific CCD cameras, which we used before. Further we can use our measuring time much more efficient, since we don’t have to care about blooming or the reduction of reflections.”

Frank Michaux, Head of PIV department, Intelligent Laser Applications GmbH

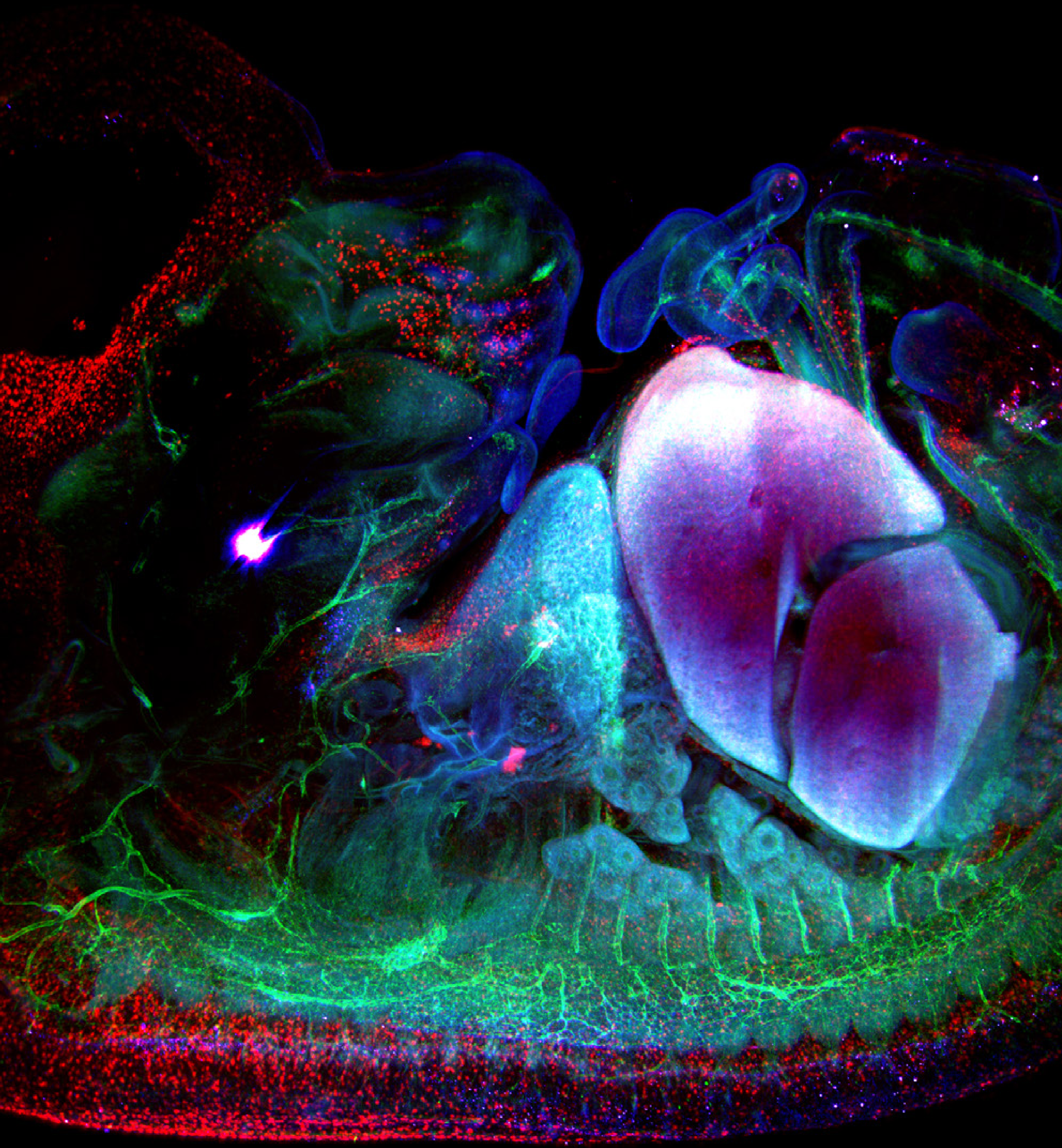


Seed particle PIV image with an overlayed vector field result image of automotive wind tunnel experiment (false color rendering) to improve the aerodynamics of a racing car.
Courtesy of Intelligent Laser Applications GmbH & Toyota Motorsport, Germany

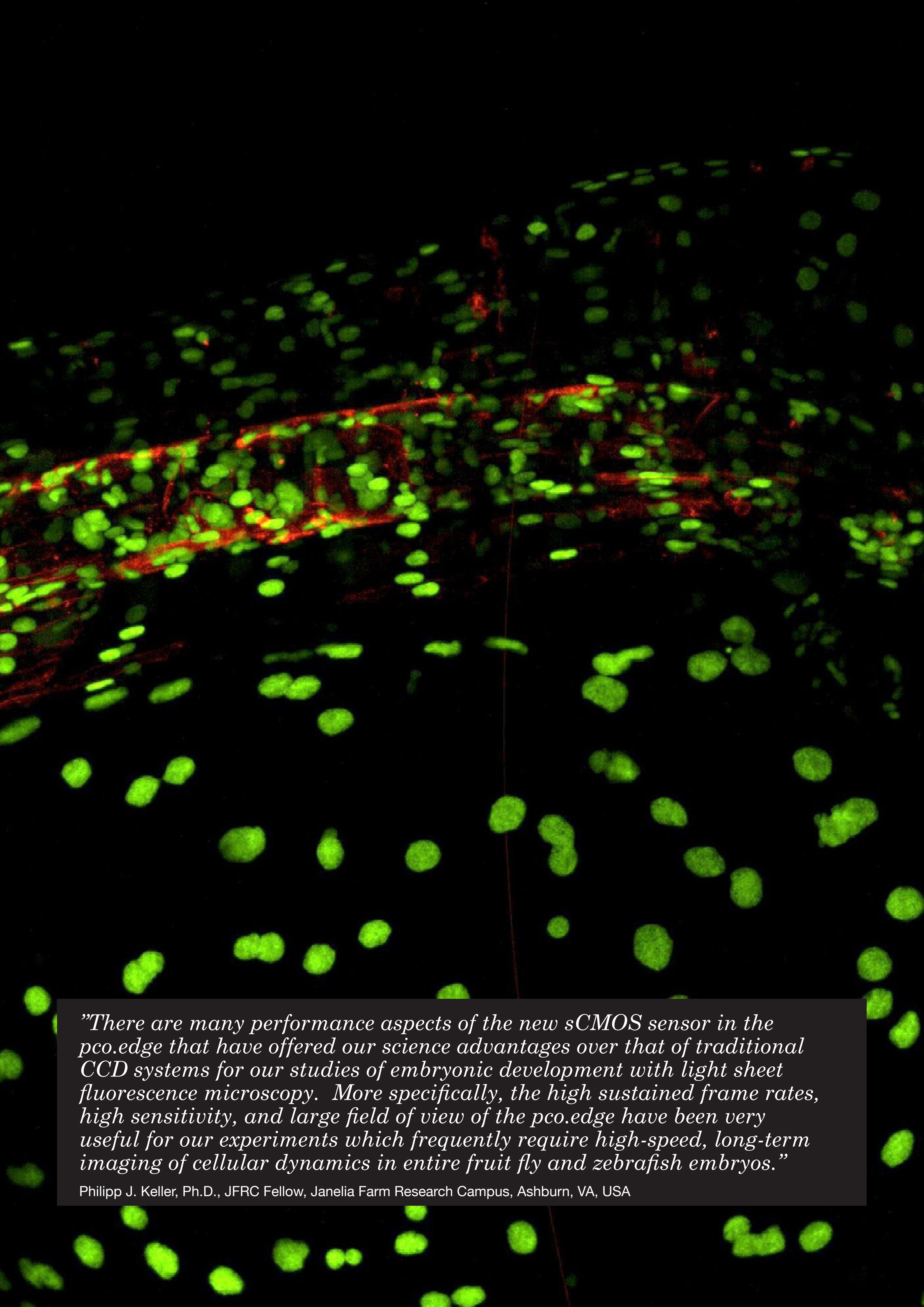


“The speed, sensitivity, and field of view of the pco.edge have been very useful for our studies of embryonic development and animal-microbe interactions, imaged using light sheet fluorescence microscopy. Our experiments, which require imaging highly dynamic cells over large volumes, would be difficult or impossible to do using traditional CCD cameras.”

Raghuveer Parthasarathy, Ph.D., Associate Professor Department of Physics, University of Oregon, OR, USA

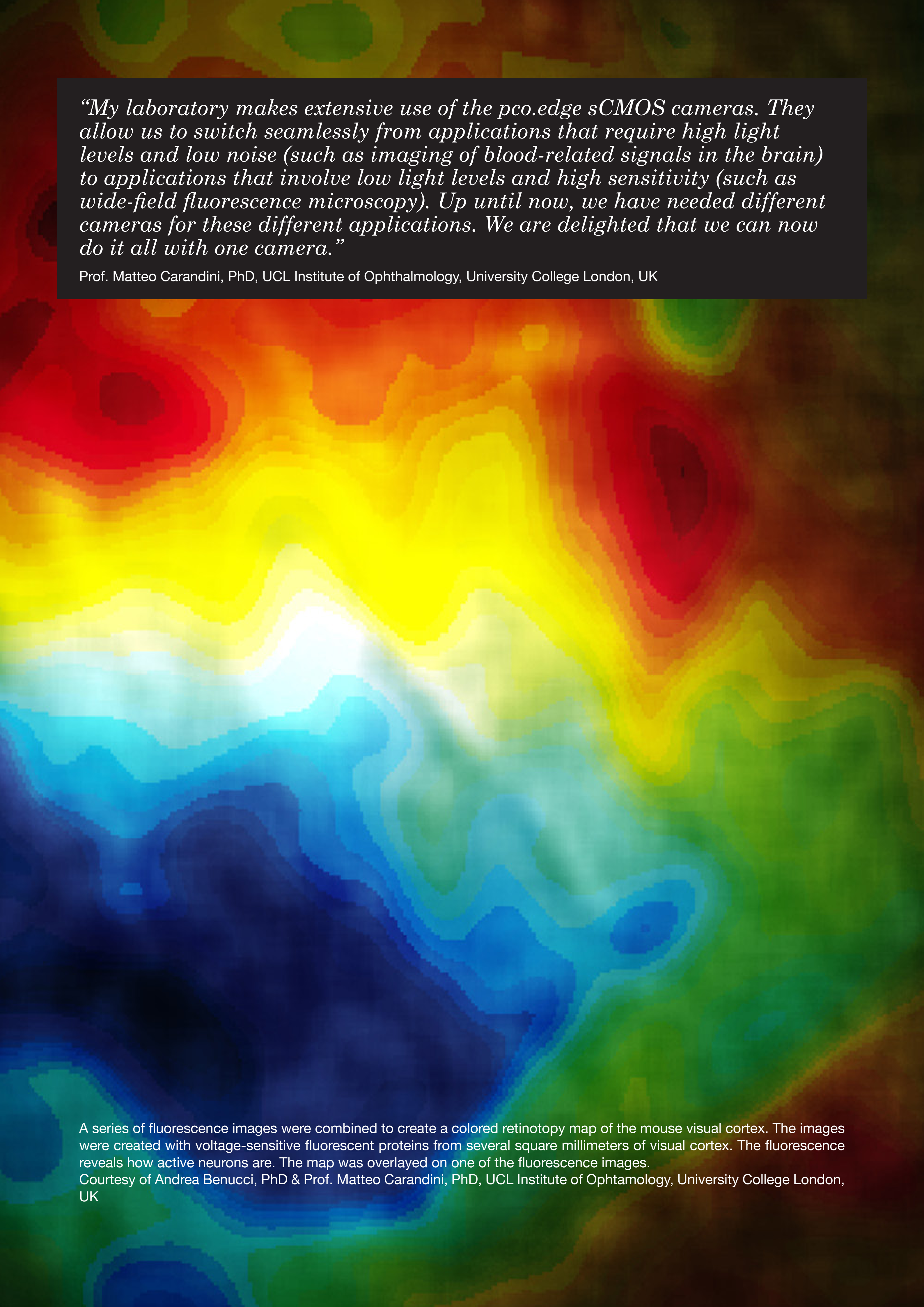


Maximum intensity projection of a mouse embryo which was obtained with a light sheet microscope (Ultramicroscope). The blood vessels were labeled with Alexa 488 (green), the neuronal structures were labeled with Alexa 568 (red) and the epithelial cells were labeled with Alexa 633 (blue).
Courtesy of LaVision BioTec GmbH, Bielefeld, Germany



"There are many performance aspects of the new sCMOS sensor in the pco.edge that have offered our science advantages over that of traditional CCD systems for our studies of embryonic development with light sheet fluorescence microscopy. More specifically, the high sustained frame rates, high sensitivity, and large field of view of the pco.edge have been very useful for our experiments which frequently require high-speed, long-term imaging of cellular dynamics in entire fruit fly and zebrafish embryos."

Philipp J. Keller, Ph.D., JFRC Fellow, Janelia Farm Research Campus, Ashburn, VA, USA

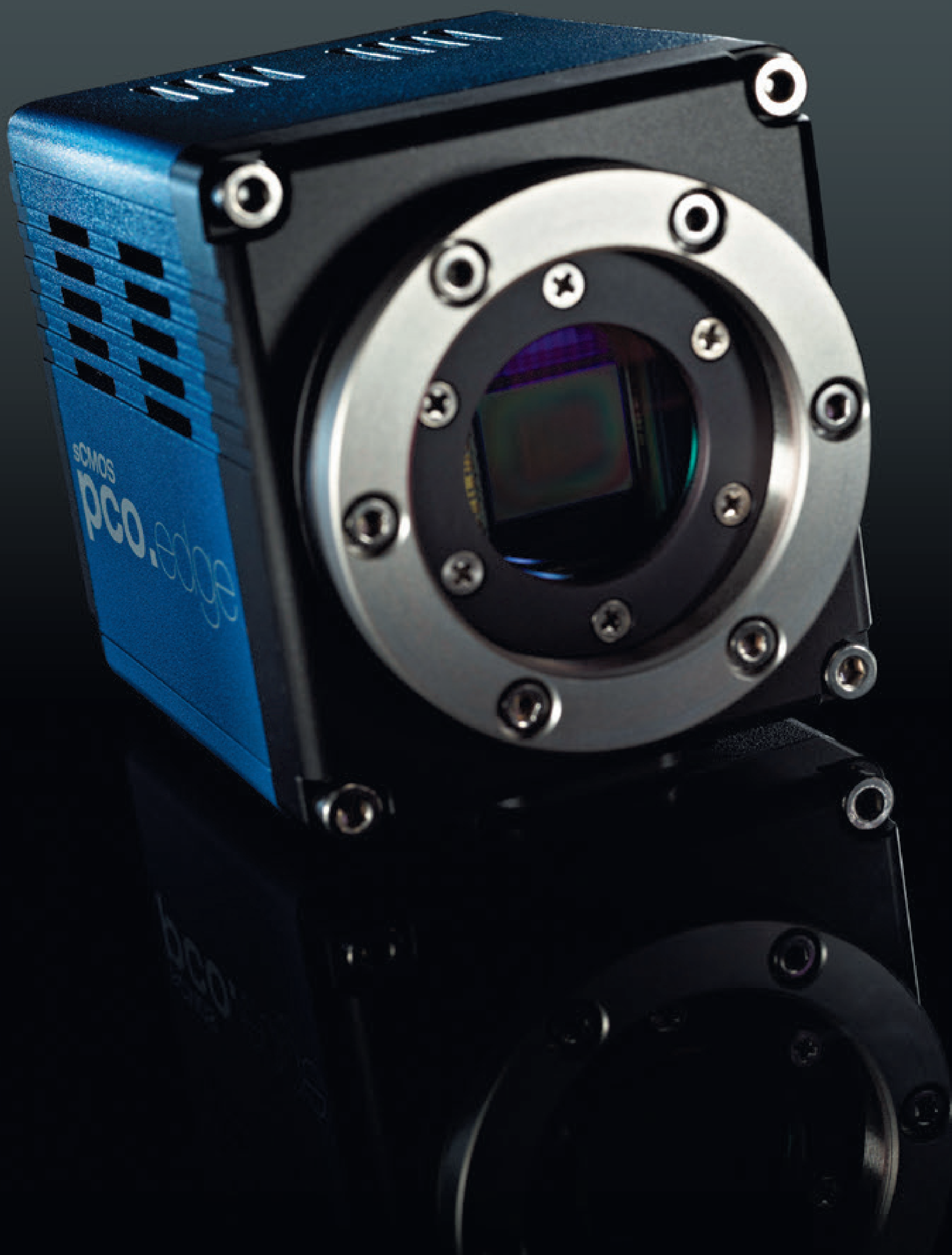


“My laboratory makes extensive use of the pco.edge sCMOS cameras. They allow us to switch seamlessly from applications that require high light levels and low noise (such as imaging of blood-related signals in the brain) to applications that involve low light levels and high sensitivity (such as wide-field fluorescence microscopy). Up until now, we have needed different cameras for these different applications. We are delighted that we can now do it all with one camera.”

Prof. Matteo Carandini, PhD, UCL Institute of Ophthalmology, University College London, UK

A series of fluorescence images were combined to create a colored retinotopy map of the mouse visual cortex. The images were created with voltage-sensitive fluorescent proteins from several square millimeters of visual cortex. The fluorescence reveals how active neurons are. The map was overlayed on one of the fluorescence images.
Courtesy of Andrea Benucci, PhD & Prof. Matteo Carandini, PhD, UCL Institute of Ophtamology, University College London, UK

TECHNICAL SPECIFICATIONS



TECHNICAL DATA

pco.edge 4.2 | Camera Link

image sensor

type of sensor	scientific CMOS (sCMOS)
image sensor	CIS2020
resolution (h x v)	2048 x 2048 active pixel
pixel size (h x v)	6.5 µm x 6.5 µm
sensor format / diagonal	13.3 mm x 13.3 mm / 18.8 mm
shutter mode	rolling shutter with free selectable readouts
MTF	76.9 lp/mm (theoretical)
fullwell capacity	30 000 e^-
readout noise[1]	0.9_{med} / 1.4_{rms} e- @ slow scan 1.0_{med} / 1.5_{rms} e- @ fast scan
dynamic range	33 000 : 1 (90.4 dB) slow scan
quantum efficiency	> 70 %
spectral range	370 nm .. 1100 nm
dark current[2]	< 0.3 e^-/pixel/s @ 5 °C
DSNU	< 1.0 e^- rms
PRNU	< 0.5 %
anti blooming factor	1 : 10 000

camera

frame rate	100 fps @ 2048 x 2048 pixel, fast scan
exposure / shutter time	500 µs .. 10 s
dynamic range A/D[4]	16 bit
A/D conversion factor	0.46 e^-/count
pixel scan rate	272.3 MHz fast scan 95.3 MHz slow scan
pixel data rate	544.6 Mpixel/s 190.7 Mpixel/s
binning horizontal	x1, x2, x4
binning vertical	x1, x2, x4
region of interest (ROI)	horizontal: steps of 1 pixel vertical: steps of 2 pixels
non linearity	< 1 %
cooling method	+ 5 °C stabilized, peltier with forced air (fan) / water cooling (up to 30°C ambient)
trigger input signals	frame trigger, sequence trigger, programmable input (SMA connectors)
trigger output signals	exposure, busy, line, programmable output (SMA connectors)
data interface	Camera Link Full (10 taps, 85 MHz)
time stamp	in image (1 µs resolution)

frame rate table

typical examples	fast scan	slow scan
2048 x 2048	100 fps	35 fps
2048 x 1024	200 fps	70 fps
2048 x 512	400 fps	140 fps
2048 x 256	800 fps	281 fps
2048 x 128	1600 fps	562 fps
1920 x 1080	189 fps	66 fps
1600 x 1200	170 fps	60 fps
1280 x 1024	200 fps	70 fps
640 x 480	426 fps	150 fps
320 x 240	853 fps	300 fps

general

power supply	12 .. 24 VDC (+/- 10 %)
power consumption	20 W max. (typ. 10 W @ 20 °C)
weight	700 g
operating temperature	+ 10 °C .. + 40 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 10 °C .. + 60 °C
optical interface	F-mount & C-mount
CE / FCC certified	yes

frame rate table extended readout mode[3]

typical examples	fast scan	slow scan
2048 + 12 x 2048	100 fps	35 fps
2048 + 12 x 1024	200 fps	70 fps

1 The readout noise values are given as median (med) and root mean square (rms) values, due to the different noise models, which can be used for evaluation. All values are raw data without any filtering.
2 Measurements with dark current compensation.
3 Extended readout mode with 12 columns of black reference pixel.
4 The high dynamic signal is simultaneously converted at high and low gain by two 11 bit A/D converters and the two 11 bit values are sophistically merged into one 16 bit value.

TECHNICAL DATA

pco.edge 4.2 | USB 3.0

image sensor

type of sensor	scientific CMOS (sCMOS)
image sensor	CIS2020
resolution (h x v)	2048 x 2048 active pixel
pixel size (h x v)	6.5 µm x 6.5 µm
sensor format / diagonal	13.3 mm x 13.3 mm / 18.8 mm
shutter mode	rolling shutter
MTF	76.9 lp/mm (theoretical)
fullwell capacity	30 000 e^-
readout noise[1]	0.9_{med} / 1.4_{rms} e-
dynamic range	33 000 : 1 (90.4 dB)
quantum efficiency	> 70 %
spectral range	370 nm .. 1100 nm
dark current[2]	< 0.3 e^-/pixel/s @ 0 °C
DSNU	< 0.3 e^- rms
PRNU	< 0.2 %
anti blooming factor	1 : 10 000

frame rate table

typical example	
2048 x 2048	40 fps

camera

frame rate	40 fps @ 2048 x 2048 pixel
exposure / shutter time	500 µs .. 10 s
dynamic range A/D[3]	16 bit
A/D conversion factor	0.46 e^-/count
pixel scan rate	110.0 MHz
pixel data rate	220.0 Mpixel/s
binning horizontal	x1, x2, x4
binning vertical	x1, x2, x4
region of interest (ROI)	horizontal: steps of 4 pixels vertical: steps of 1 pixel
non linearity	< 0.6 %
cooling method	0 °C stabilized, peltier with forced air (fan) / water cooling (up to 30°C ambient)
trigger input signals	frame trigger, programmable input (SMA connectors)
trigger output signals	exposure, busy, line, programmable output (SMA connectors)
data interface	USB 3.0
time stamp	in image (1 µs resolution)

general

power supply	12 .. 24 VDC (+/- 10 %)
power consumption	21 W max. (typ. 12 W @ 20 °C)
weight	930 g
operating temperature	+ 10 °C .. + 40 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 10 °C .. + 60 °C
optical interface	F-mount & C-mount
CE / FCC certified	yes

[1] The readout noise values are given as median (med) and root mean square (rms) values, due to the different noise models, which can be used for evaluation. All values are raw data without any filtering.
[2] Measurements with dark current compensation.
[3] The high dynamic signal is simultaneously converted at high and low gain by two 11 bit A/D converters and the two 11 bit values are sophistically merged into one 16 bit value.

TECHNICAL DATA

pco.edge 5.5 | Camera Link

image sensor

type of sensor	scientific CMOS (sCMOS)
image sensor	CIS2521
resolution (h x v)	2560 x 2160 pixel
pixel size (h x v)	6.5 µm x 6.5 µm
sensor format / diagonal	16.6 mm x 14.0 mm / 21.8 mm
shutter modes	rolling shutter (RS) with free selectable readouts, global/snapshot shutter (GS), global reset - rolling readout (GR)
MTF	76.9 lp/mm (theoretical)
fullwell capacity	30 000 e-
readout noise[1]	1.1_{med} / 1.5_{rms} e- @ RS, slow scan 1.5_{med} / 1.7_{rms} e- @ RS, fast scan 2.2_{med} / 2.5_{rms} e- @ GS, fast scan
dynamic range	27 000 : 1 (88.6 dB) RS, slow scan
quantum efficiency	> 60 %
spectral range	370 nm .. 1100 nm
dark current[2]	< 0.3 e-/pixel/s RS @ 5 °C < 0.5 e-/pixel/s GS @ 5 °C
DSNU	< 1.0 e- rms
PRNU	< 0.5 %
anti blooming factor	1 : 10 000

frame rate table

typical examples	RS fast scan	GS fast scan	RS slow scan
2560 x 2160	100 fps	50 fps	33 fps
2560 x 1024	212 fps	105 fps	70 fps
2560 x 512	422 fps	208 fps	140 fps
2560 x 256	838 fps	409 fps	279 fps
2560 x 128	1651 fps	789 fps	550 fps
1920 x 1080	201 fps	100 fps	67 fps
1600 x 1200	181 fps	90 fps	60 fps
1280 x 1024	212 fps	105 fps	70 fps
640 x 480	450 fps	222 fps	150 fps
320 x 240	893 fps	436 fps	297 fps

[1] The readout noise values are given as median (med) and root mean square (rms) values, due to the different noise models, which can be used for evaluation. All values are raw data without any filtering.
[2] Measurements with dark current compensation.
[3] The high dynamic signal is simultaneously converted at high and low gain by two 11 bit A/D converters and the two 11 bit values are sophistically merged into one 16 bit value.
[4] Visually lossless compression / decompression for data transfer in fast scan mode and horizontal resolution greater than 1920 pixel (due to Camera Link limitations).

camera

frame rate[2] @ 2560 x 2160 pixel	100 fps @ RS, fast scan 50 fps @ GS, fast scan
exposure / shutter time	500 µs .. 2 s RS 10 µs .. 100 ms GS 10 µs .. 2 s GR
dynamic range A/D[3, 4]	16 bit
A/D conversion factor	0.46 e-/count
pixel scan rate	286.0 MHz fast scan 95.3 MHz slow scan
pixel data rate	572.0 Mpixel/s 190.7 Mpixel/s
binning horizontal	x1, x2, x4
binning vertical	x1, x2, x4
region of interest (ROI)	horizontal: steps of 4 pixels vertical: steps of 2 pixels
non linearity	< 1 %
cooling method	+ 5 °C stabilized, peltier with forced air (fan) / water cooling (up to 30°C ambient)
trigger input signals	frame trigger, sequence trigger, programmable input (SMA connectors)
trigger output signals	exposure, busy, line, programmable output (SMA connectors)
data interface	Camera Link Full (10 taps, 85 MHz)
time stamp	in image (1 µs resolution)

general

power supply	12 .. 24 VDC (+/- 10 %)
power consumption	20 W max. (typ. 10 W @ 20 °C)
weight	700 g
operating temperature	+ 10 °C .. + 40 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 10 °C .. + 60 °C
optical interface	F-mount & C-mount
CE / FCC certified	yes

TECHNICAL DATA

pco.edge 5.5 | USB 3.0

image sensor

type of sensor	scientific CMOS (sCMOS)
image sensor	CIS2521
resolution (h x v)	2560 x 2160 pixel
pixel size (h x v)	6.5 µm x 6.5 µm
sensor format / diagonal	16.6 mm x 14.0 mm / 21.8 mm
shutter modes	rolling shutter (RS)
MTF	76.9 lp/mm (theoretical)
fullwell capacity	30 000 e^-
readout noise[1]	1.1_{med} / 1.5_{rms} e-
dynamic range	27 000 : 1 (88.6 dB)
quantum efficiency	> 60 %
spectral range	370 nm .. 1100 nm
dark current[2]	< 0.3 e^-/pixel/s @ 0 °C
DSNU	< 0.3 e^- rms
PRNU	< 0.2 %
anti blooming factor	1 : 10 000

camera

frame rate	32 fps @ 2560 x 2160 pixel
exposure / shutter time	500 µs .. 2 s
dynamic range A/D[3]	16 bit
A/D conversion factor	0.46 e^-/count
pixel scan rate	86.0 MHz
pixel data rate	172.0 Mpixel/s
binning horizontal	x1, x2, x4
binning vertical	x1, x2, x4
region of interest (ROI)	horizontal: steps of 4 pixels vertical: steps of 1 pixel
non linearity	< 0.6 %
cooling method	0 °C stabilized, peltier with forced air (fan) / water cooling (up to 30°C ambient)
trigger input signals	frame trigger, programmable input (SMA connectors)
trigger output signals	exposure, busy, line, programmable output (SMA connectors)
data interface	USB 3.0
time stamp	in image (1 µs resolution)

frame rate table

typical example	
2560 x 2160	32 fps

general

power supply	12 .. 24 VDC (+/- 10 %)
power consumption	21 W max. (typ. 12 W @ 20 °C)
weight	930 g
operating temperature	+ 10 °C .. + 40 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 10 °C .. + 60 °C
optical interface	F-mount & C-mount
CE / FCC certified	yes

[1] The readout noise values are given as median (med) and root mean square (rms) values, due to the different noise models, which can be used for evaluation. All values are raw data without any filtering.
[2] Measurements with dark current compensation.
[3] The high dynamic signal is simultaneously converted at high and low gain by two 11 bit A/D converters and the two 11 bit values are sophistically merged into one 16 bit value.

TECHNICAL DATA

SOFTWARE

Camware is provided for camera control, image acquisition and archiving of images in various file formats (WindowsXP and later). A free software development kit (SDK) including a dynamic link library, for user customization, integration on PC platforms is available. Drivers for popular third party software packages are also available.
(Please visit www.pco.de for more information)

The pco water cooling unit.

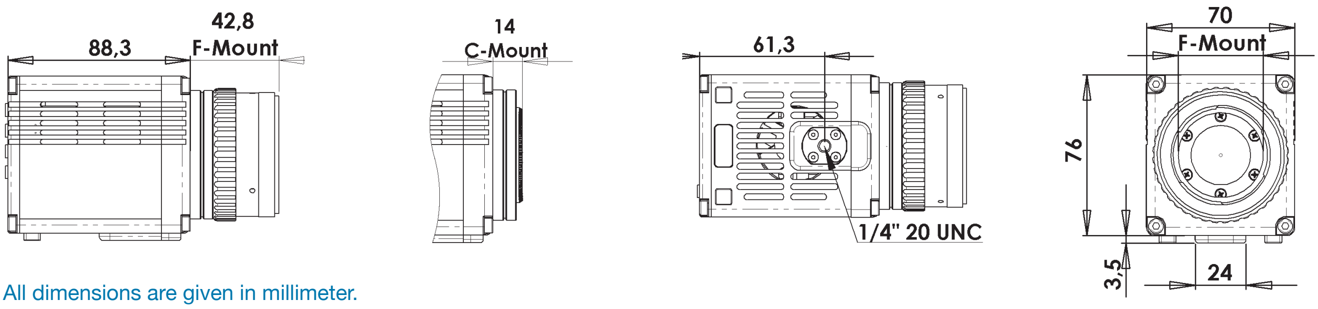
OPTIONS

monochrome & color versions available; custom made versions (e.g. water cooling, deep cooled...)

1288 EMVA Standard Compliant

DIMENSIONS

F-mount and c-mount lens changeable adapter.



All dimensions are given in millimeter.

CAMERA VIEWS

USB 3.0

pco.edge water cooled

Camera Link

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