ORCA®-Quest2

qCMOS® camera C15550-22UP

Photon number resolving

HAMAMATSU

PHOTON IS OUR BUSINESS

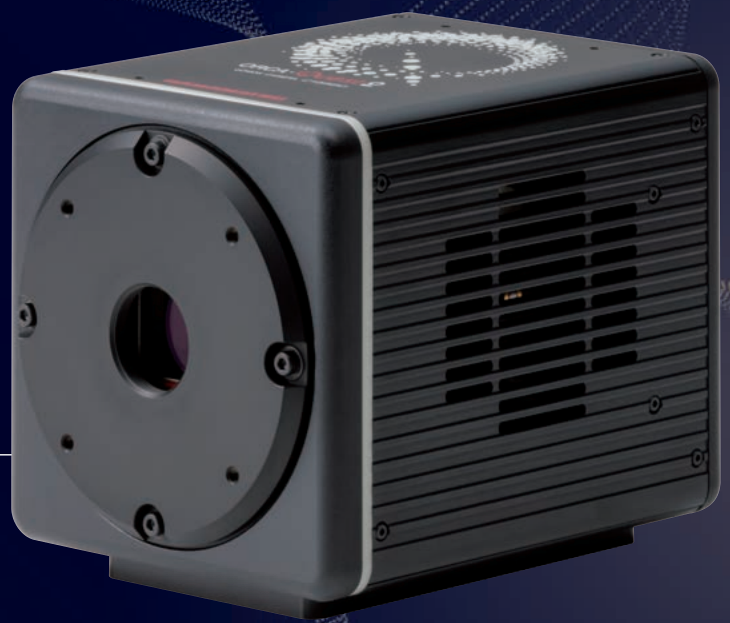
Achieves the ultimate in quantitative imaging.

Since the 1980s, Hamamatsu Photonics has continued to develop high-sensitivity, low-noise cameras using its unique camera design technology and has always contributed to the development of cutting-edge scientific and technological research.

With over 40 years of experience, in 2021, Hamamatsu Photonics are proud to have released the ORCA-Quest with ultimate performance.

The world's first qCMOS camera

ORCA-Quest

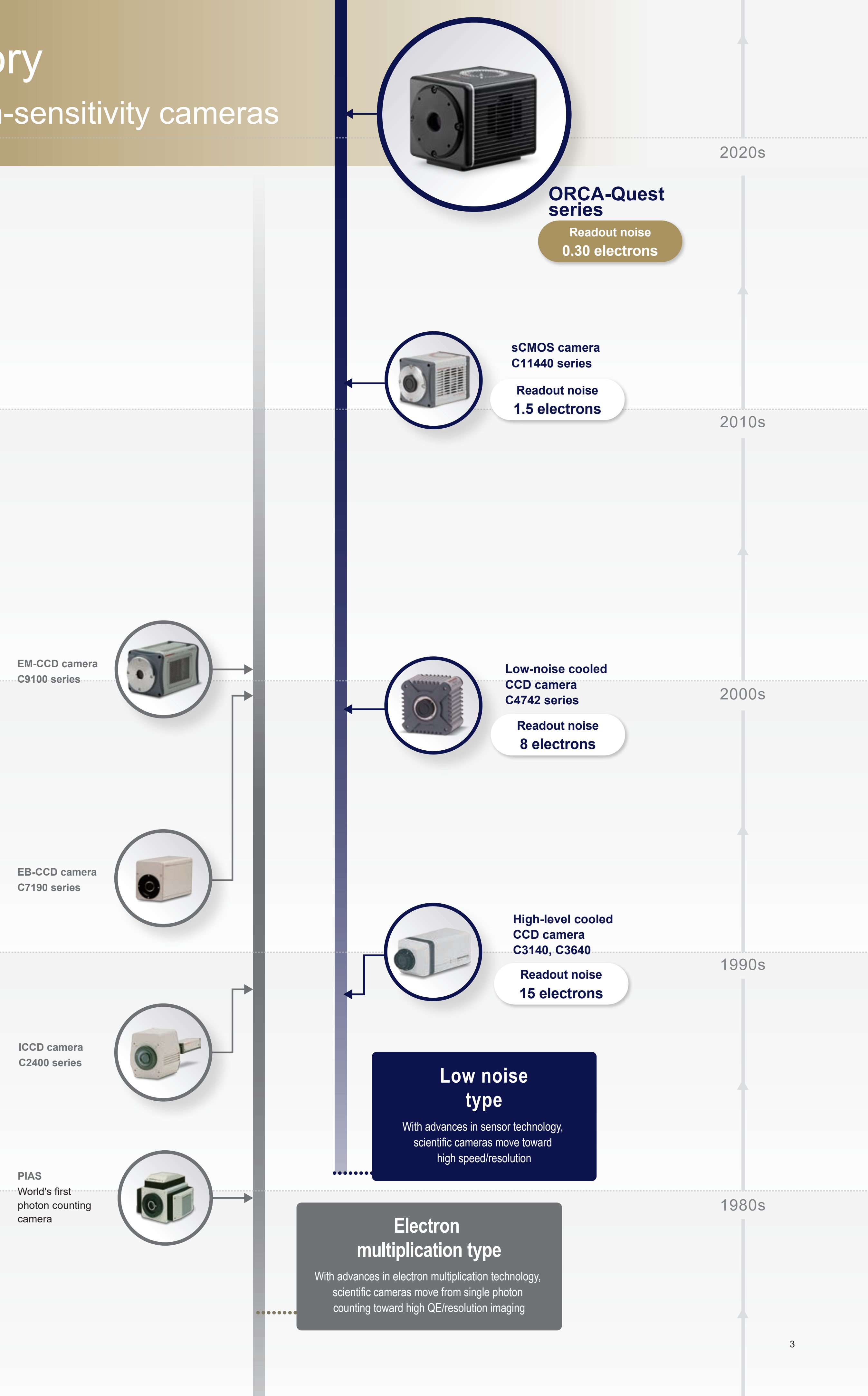


Evolution from single photon counting to photon number resolving

What is qCMOS?

The qCMOS (Quantitative CMOS) is a CMOS image sensor that has the ability to detect and identify the number of both single and multiple photoelectrons.
ORCA-Quest is the world's first camera to incorporate the qCMOS image sensor and to be able to resolve the number of photoelectrons using a newly developed dedicated technology. (See page 8)

History of high-sensitivity cameras



The evolution of qCMOS continues

ORCA-Quest 2

Evolution from ORCA-Quest

LOW READOUT NOISE AND HIGH SPEED

0.30 ELECTRONS RMS @ 25 fps*
ULTRA QUIET SCAN

0.43 ELECTRONS RMS @ 120 fps*
STANDARD SCAN

HIGH RESOLUTION

4096 × 2304
9.4 MEGAPIXELS

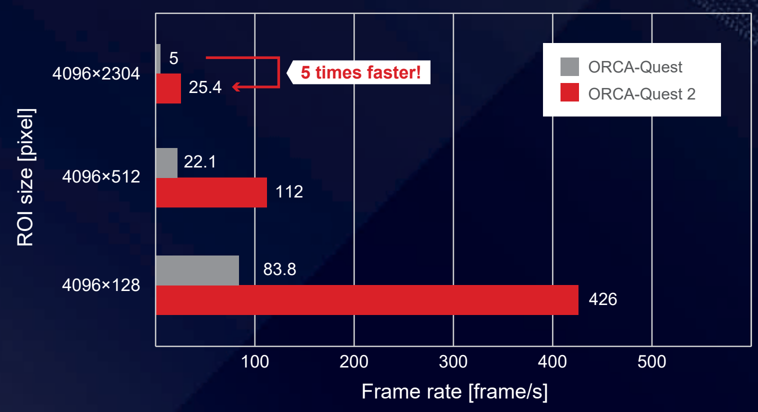
HIGH QE

50 % @300 nm
85 % @460 nm
30 % @900 nm

* Frame rate value in full resolution

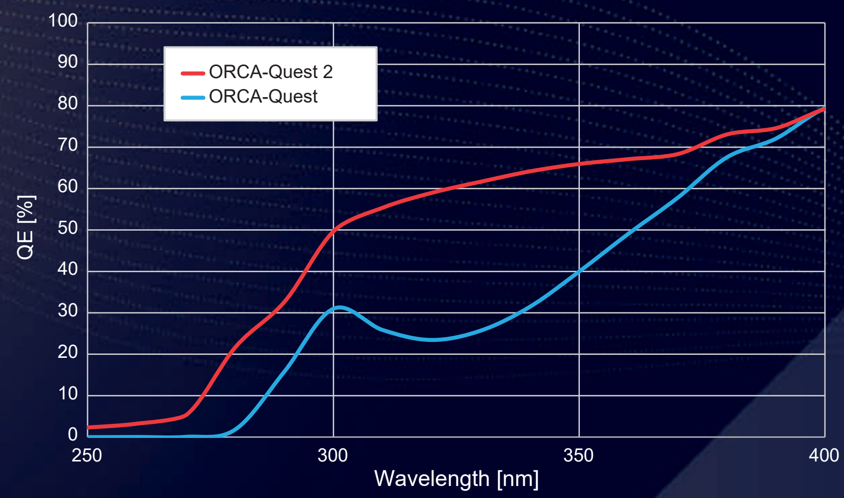
Faster ultra quiet scan mode

ORCA-Quest had achieved the level to realize photon number resolving owing to ultra-low noise characteristic in ultra quiet scan mode. However, this availability was limited for users because the ultra-low noise was available only when the camera operated in 5 frame per second (in full resolution). ORCA-Quest 2 has achieved 5 times faster framerate with a similar ultra-low noise characteristic by optimizing the sensor operation. Photon number resolving feature has become available for most of users now!



UV QE improvement

ORCA-Quest possessed high quantum efficiency (QE) in UV region around 280 nm-400 nm, compared to most of conventional scientific cameras.
Inspired by market needs, ORCA-Quest 2 has achieved even higher UV QE by optimizing AR coating of the sensor window, with no change of visible, near infrared wavelength region. The QE improvement expands the versatility of ORCA-Quest series in many kinds of application such as trapped ion quantum experiment.



Raw data output

The feature allows you to apply any algorithms to estimate the number of photoelectron from raw digital signal.

Faster edge trigger mode

The new edge trigger mode enables you to input an external trigger and start exposure during rolling shutter readout, resulting in a faster frame rate.

Four key features

that enable the ORCA-Quest 2 to achieve ultimate quantitative imaging

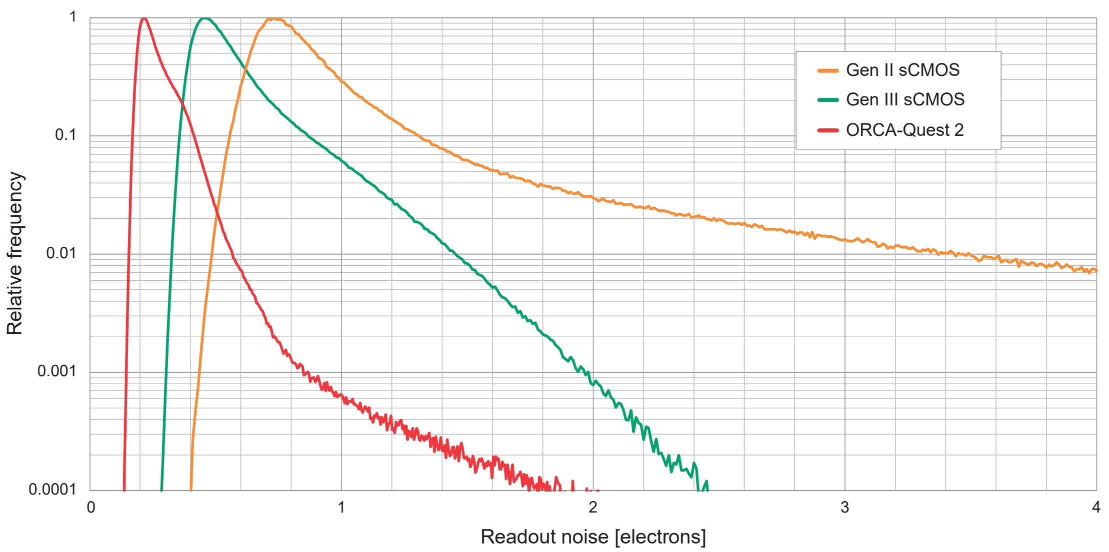
1. Extreme low-noise performance
2. Realization of photon number resolving (PNR) output
3. Back-illuminated structure and high resolution
4. Realization of a large number of pixels and high speed readout

1. Extreme low-noise performance

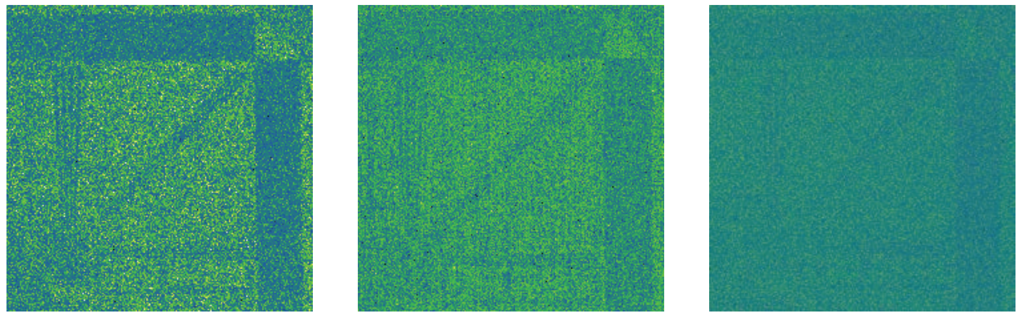
Ultra-low readout noise 0.30 electrons rms

at Ultra quiet scan

In order to detect weak light with high signal-to-noise, ORCA-Quest 2 has been designed and optimized to every aspect of the sensor from its structure to its electronics. Not only the camera development but also the custom sensor development has been done with latest CMOS technology, an extremely low noise performance of 0.30 electrons has been achieved.



qCMOS (ORCA-Quest 2) **Gen III sCMOS** **Gen II sCMOS**



Comparison of average 1 photon per pixel image (pseudo-color)
Exposure time: 200 ms LUT: minimum to maximum value Comparison area: 512 pixels × 512 pixels

Low-dark current 0.006 electrons/pixel/s

at −35 °C

In the field of single photon counting and photon number resolving, even dark currents as low as 0.5 electrons/pixel/s can affect photon detection. The 0.006 electrons/pixel/s @−35 °C value achieved by ORCA-Quest 2 is an extremely low probabilistic value of only 1 electrons of dark current generated in approximately 167 pixels when exposed for 1 second.
Thus, the ORCA-Quest 2, which is less affected by dark current, is ideal for quantitative imaging and analysis.

ORCA-Quest 2 **Gen II sCMOS camera**

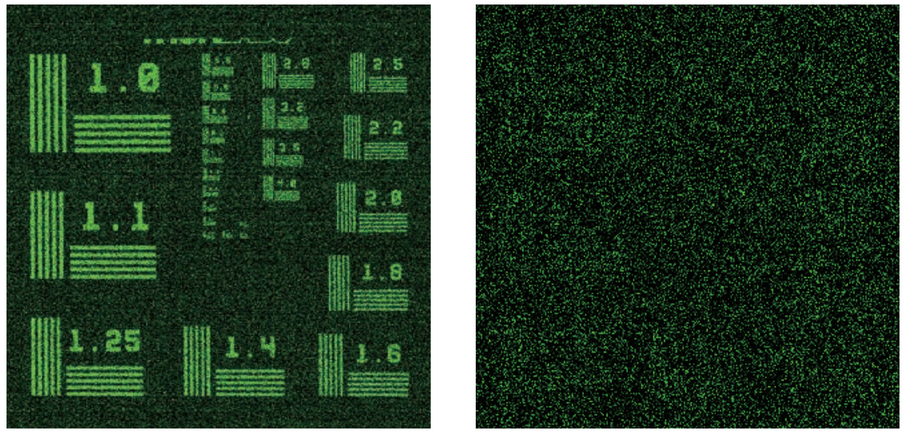


Image quality comparison at long exposure time (pseudo-color)
Incident light intensity: 0.05 photons/pixel/s Exposure time: 15 min (10 s × 90 times integration)

Cosmic-ray effects in long-time exposure

When performing long-time exposure, conventional EM-CCD cameras are easily affected by cosmic rays, and the resulting white spots have become a problem. ORCA-Quest 2 is not easily affected by cosmic rays and can suppress the deterioration of image quality due to white spots during long-time exposure.

ORCA-Quest 2 **EM-CCD camera**

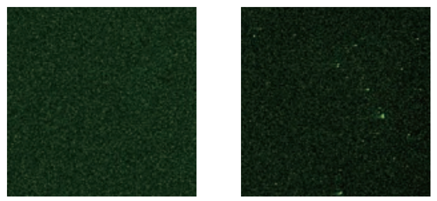


Image quality comparison at long exposure time (pseudo-color)
No incident light Exposure time: 30 min

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2. Realization of photon number resolving (PNR) output

Realization of photon number resolving by low-readout noise

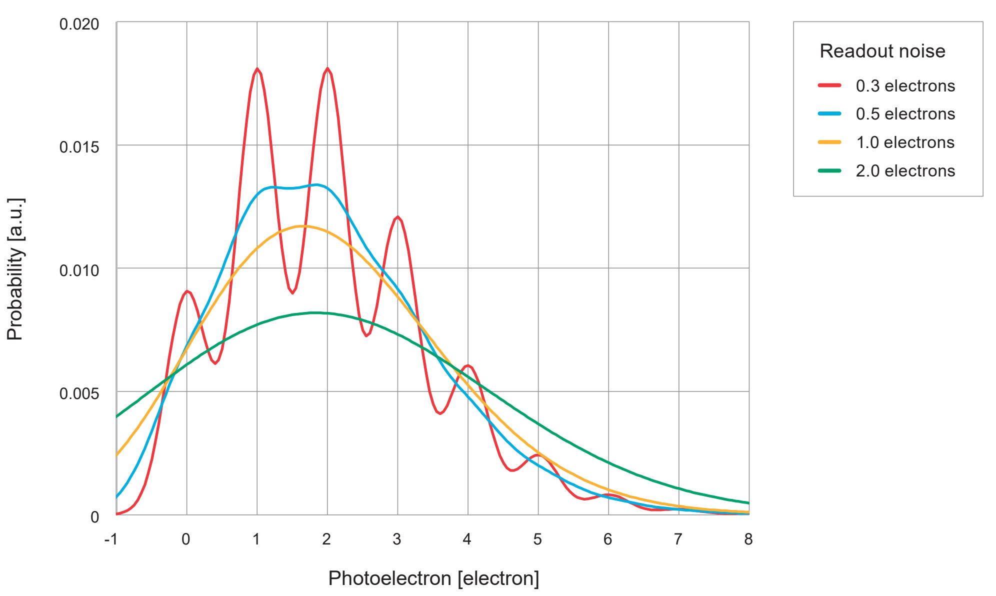
Light is a collection of many photons. Photons are converted into electrons on the sensor, and these electrons are called photoelectrons. “Photon number resolving” is a method of accurately measuring light by counting photoelectrons.*

In order to count these photoelectrons, camera noise must be sufficiently smaller than the amount of photoelectron signal. Conventional sCMOS cameras achieve a small readout noise, but still larger than photoelectron signal, making it difficult to count photoelectrons.

Using advanced camera technology, the ORCA-Quest 2 counts photoelectrons and delivers an ultra-low readout noise of 0.30 electrons rms (@Ultra quiet scan), stability over temperature and time, individual calibration and real-time correction of each pixel value.

For more information about the qCMOS image sensor, please refer to the ORCA-Quest white paper.

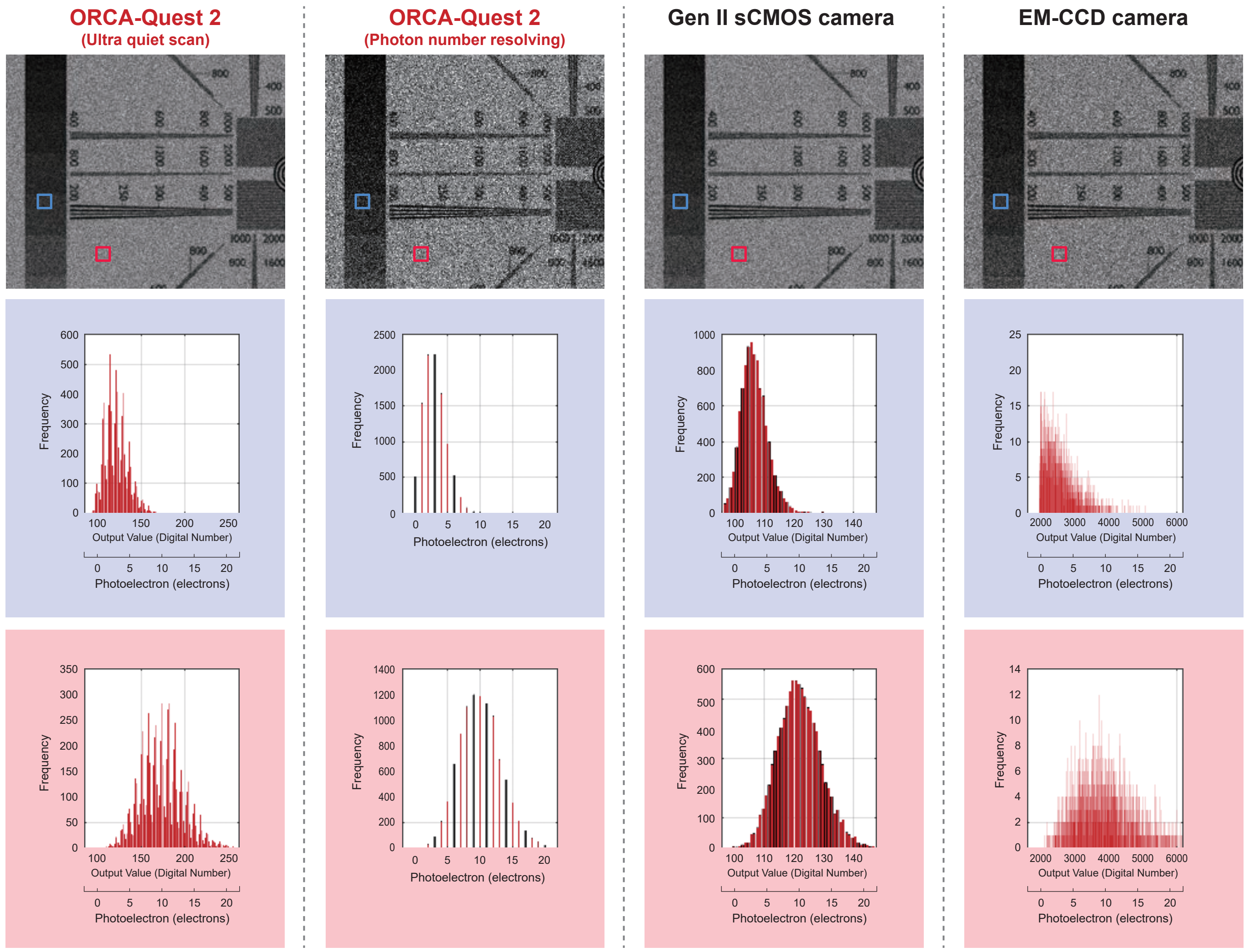
Simulation data of photoelectron probability distribution (Average number of photoelectrons generated per pixel: 2 electrons)



* Photon number resolving is unique and quite different from photon counting (More precisely the method resolves the number of photoelectrons. However, since single photon counting instead of single photoelectron counting has been used for a comparable method in this field, we will use the term “photon number resolving” in this brochure).

Spatial photon number resolving capability

The graphs show simulated histograms when averaged photoelectrons are 3 and 10 electrons/pixel.
While the EM-CCD and Gen II sCMOS cameras cannot realize the photon number resolving due to multiplication noise or higher readout noise, the ORCA-Quest 2 realizes spatial photon number resolving in addition to temporal photon number resolving.
Furthermore, it follows Poisson distributions corresponding with averaged photoelectrons of 3 and 10 electrons/pixel.



Average number of photoelectrons generated per pixel: 3 electrons
Average number of photoelectrons generated per pixel: 10 electrons

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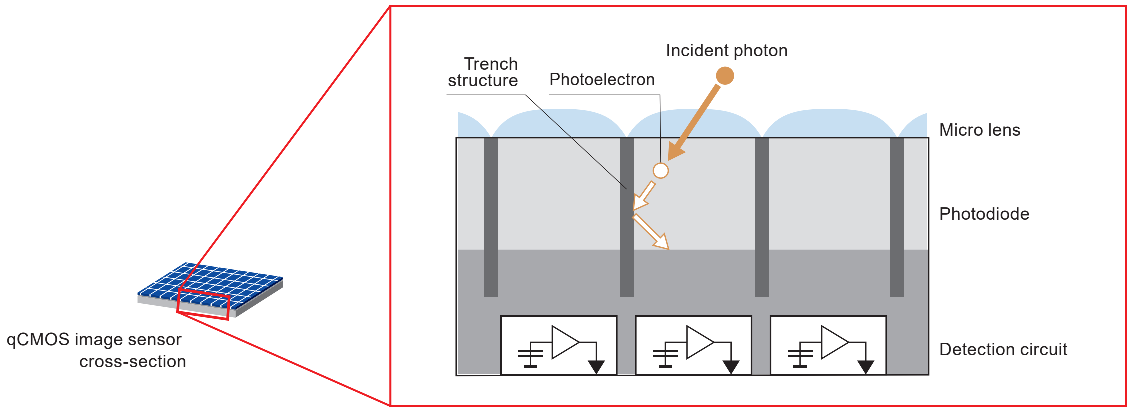
3. Back-illuminated structure and high resolution

Trench structure to suppress crosstalk

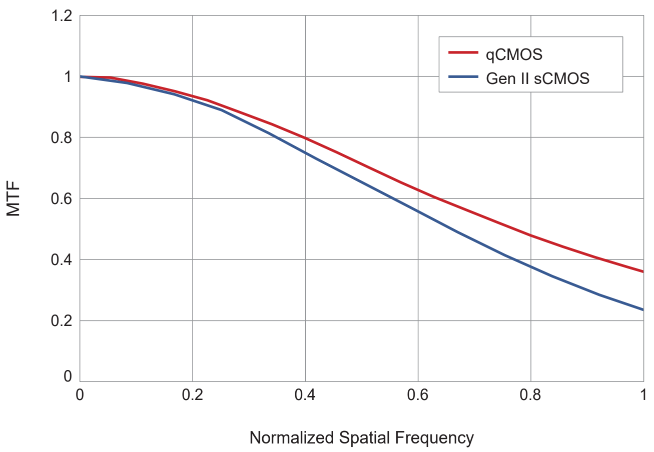
High QE is essential for high efficiency of detecting photons and achieved by back-illuminated structure.
In conventional back-illuminated sensors, crosstalks occur between pixels due to no pixel separation, and resolutions are usually inferior to those of front-illuminated sensors. The ORCA-Quest 2 qCMOS's sensor has back-illuminated structure for achieving high quantum efficiency, and trench structure in one-by-one pixel for reducing crosstalk.

What is a trench structure?



The trench structure suppresses the flow of photoelectrons to neighboring pixels.

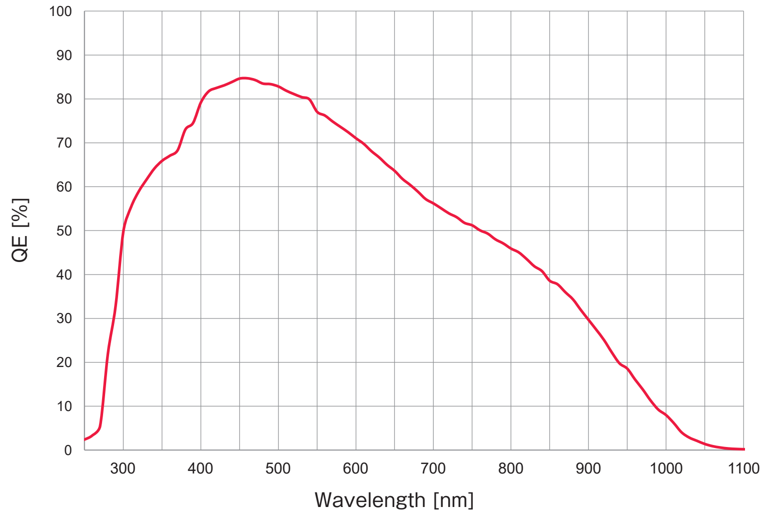
Measurement result of MTF



Modulation Transfer Function (MTF) is a type of resolution evaluation. It is the value of how accurately the contrast of an object can be reproduced.

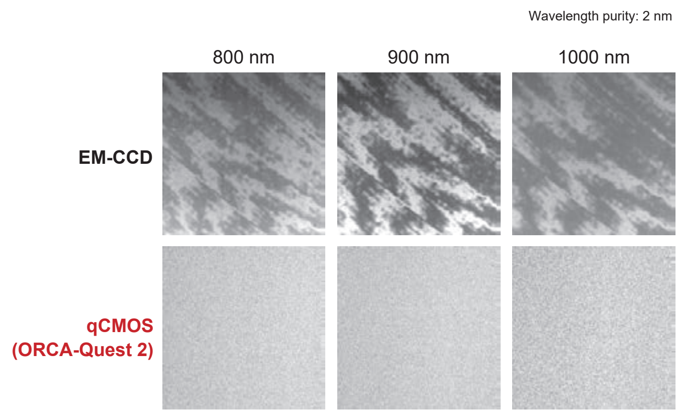
High QE 50 % @300 nm, 85 % @460 nm, 30 % @900 nm

It also has high quantum efficiency in the near-infrared region because of its thicker layer of the charge detection region.
Normally, there is a trade-off between the thickness of the layer of the photon detection region and the resolution, but the trench structure suppresses the degradation of the resolution.



Etaloning-desensitized

Etaloning is a phenomenon that occurs when the incident light interferes with the reflected light from the back surface of the silicon and causes varying sensitivity dependent both on the spatial and the spectral position. In the case of an EM-CCD camera, it appears as a fringe pattern even with uniform monochrome light input, mostly in the IR.
The qCMOS camera shows minimal etaloning compared to EM-CCD cameras.



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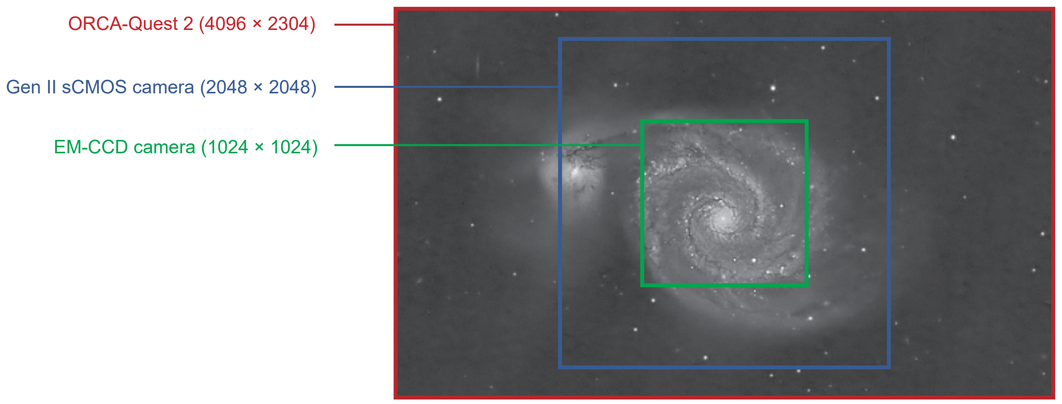
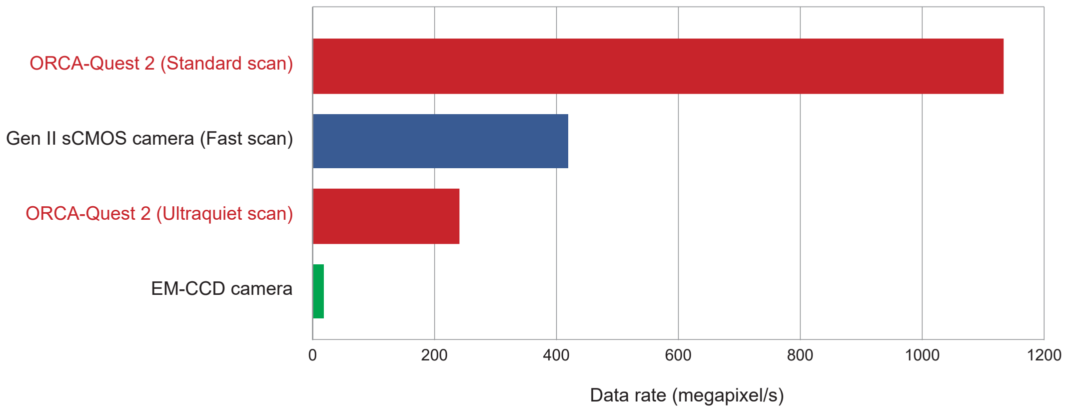
Coexistence of quantitative imaging, many pixels, and high speed

ORCA-Quest 2 realizes ultra-low noise with 9.4 megapixels (4096 (H) × 2304 (V)). ORCA-Quest 2 is capable of capturing a larger number of objects, compared to conventional scientific cameras like Gen II sCMOS and EM-CCD camera.



In addition, ORCA-Quest 2 has outstanding performance in terms of its readout speed. Here, we refer to "data rate (number of pixels × frame rate)" , which represents how many pixels a camera read out in 1 second, for comparison among scientific cameras. ORCA-Quest 2 with Standard scan realizes higher data rate even with lower readout noise than conventional sCMOS cameras. Also, ORCA-Quest 2 with Ultraquiet scan realizes photon number resolving imaging with 10 times faster data rate than single photon counting imaging by EM-CCD cameras.



Fast readout speed available with subarray

Faster frame rate is available in ORCA-Quest 2 with subarray function (ROI).

Readout speed (frames/s) in Area Readout Mode

Standard scan

Number of pixels		Readout speed (frames/s)		
X (pixels)	Y (pixels)	CoaXPress	USB3.1 Gen I (16 bit)	USB3.1 Gen I (8 bit)
4096	2304	120	17.6	35.3
4096	2048	134	19.9	39.8
4096	1024	268	39.6	79.3
4096	512	532	78.9	157
4096	256	1040	156	312
4096	128	2012	304	609
4096	64	3750	583	1160
4096	32	6610	1060	2130
4096	16	10 600	1850	3650
4096	8	15 400	2890	5780
4096	4	19 800	4080	8160

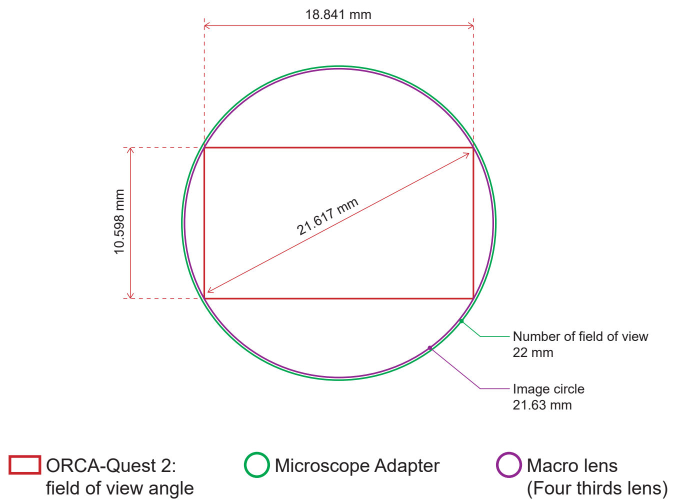
Ultra quiet scan

Number of pixels		Readout speed (frames/s)		
X (pixels)	Y (pixels)	CoaXPress	USB3.1 Gen I (16 bit)	USB3.1 Gen I (8 bit)
4096	2304	25.4	17.6	25.4
4096	2048	28.6	19.9	28.6
4096	1024	56.9	39.6	56.9
4096	512	112	78.7	112
4096	256	221	155	221
4096	128	426	303	426
4096	64	796	577	796
4096	32	1400	1050	1400
4096	16	2260	1840	2260
4096	8	3270	2670	3270
4096	4	4200	3680	4200

Sensor sizes that can be used with general-purpose optical systems

As the number of pixels increases, the size of the sensor also increases, resulting in cases where the peripheral field of view is missing when using optics such as under a microscope. The ORCA-Quest 2 has 18.841 mm (H) × 10.598 mm (V) by 9.4 megapixels, 4.6 μm px size, that fits in a C-mount of dia. 25.4 mm, making it suitable for use with general-purpose optics.

* An F-mount option is also available.



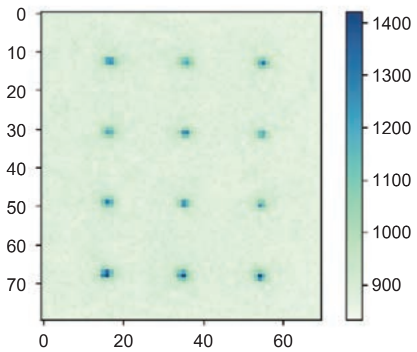
Application and Measurement Examples

Quantum technology

Neutral atom, Trapped ion

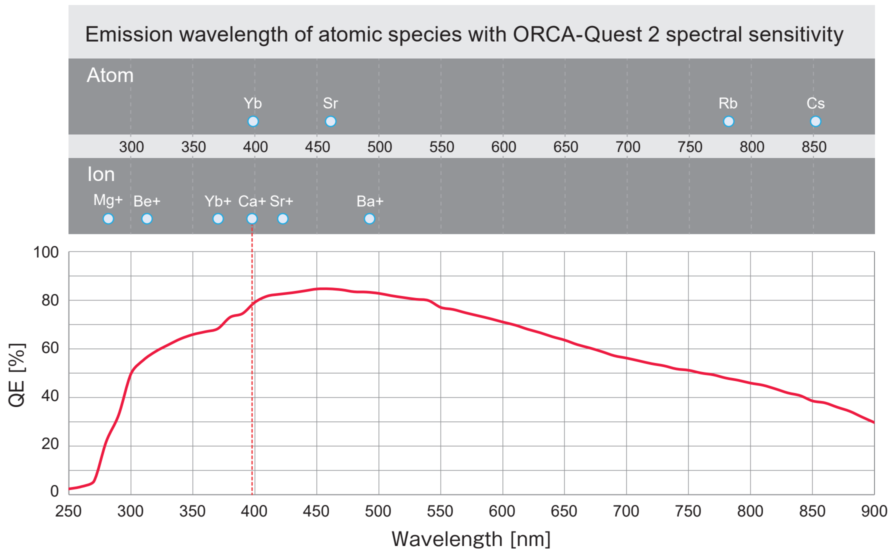
Neutral atoms and ions are aligned one by one in an array to be utilized as Qubits for Quantum computing. The qubit states can be determined by observing the fluorescence from each of them. The measurement of the fluorescence needs to be done in short time and then photodetectors with very low noise and high speed are needed. ORCA-Quest 2 can do both of diagnosis of the whole qubit array and state detection of each qubit with very low noise characteristics and high speed readout. Also, the QE covers wide range of wavelength for major ion and atom species.

Fluorescence imaging of Rb atom array with ORCA-Quest



Data courtesy of Prof.Takashi Yamamoto and Associate Prof. Toshiki Kobayashi, Osaka University

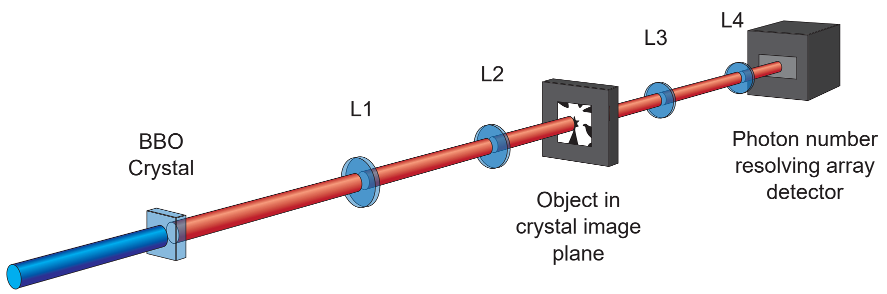
Reference : https://camera.hamamatsu.com/all/en/application_and_case_study/quantum_technology/Imaging_single_atom_array_by_orca_quest.html

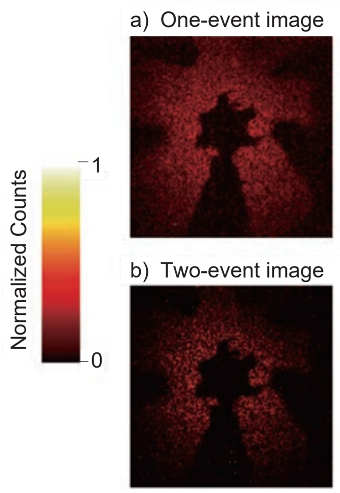


Quantum optics

Quantum optics uses single photon sources to make use of the Quantum nature of the single photon.
The quantum optics research also uses single photon counting detectors, and now there are emerging needs of photon number resolving detectors to distinguish photon numbers coming into the detectors.
A photon counting camera, a new concept in camera technologies, is expected to make a new discovery in this field.

Experimental setup and images of Quantum imaging with ORCA-Quest





Data courtesy of Prof. Miles Padgett, University of Glasgow
Reference : https://www.nature.com/articles/s41598-022-10037-x

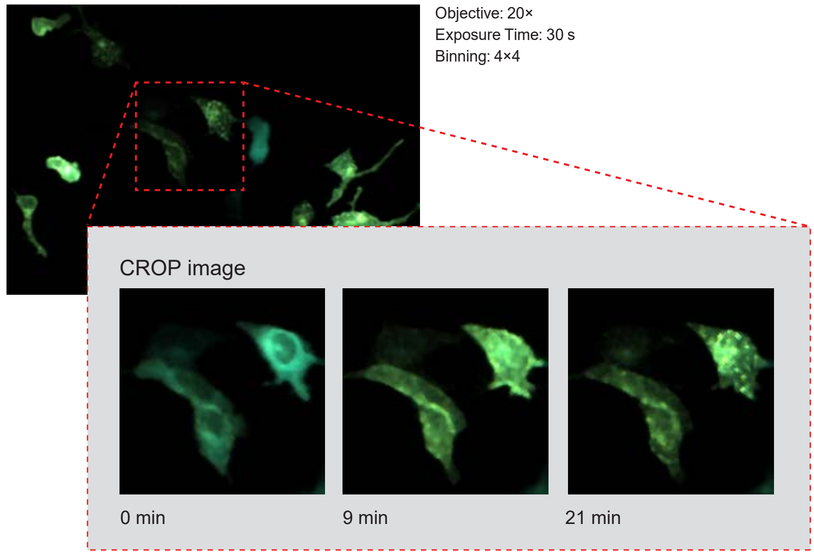
Life science

Bioluminescence

Bioluminescence microscopy has been gaining attentions because of the unique advantages against the conventional fluorescence microscopy, such as no need of excitation light.
The major drawback of the bioluminescence is its very low light intensity, resulting in long exposure time and low image quality.
The bioluminescence research needs highly sensitive cameras even in long exposure.

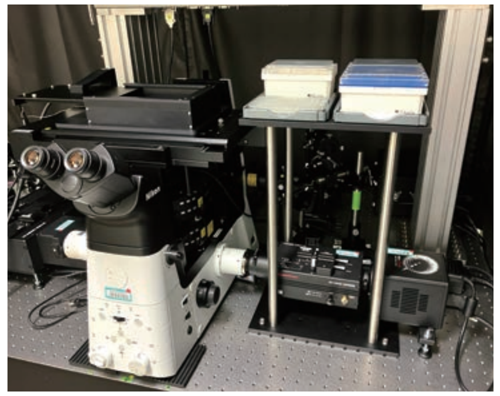
Simultaneous dual wavelength luminescence imaging (ORCA-Quest + W-VIEW GEMINI)

Overall image in the field of view



Objective: 20×
Exposure Time: 30 s
Binning: 4×4

Appearance of the microscope system



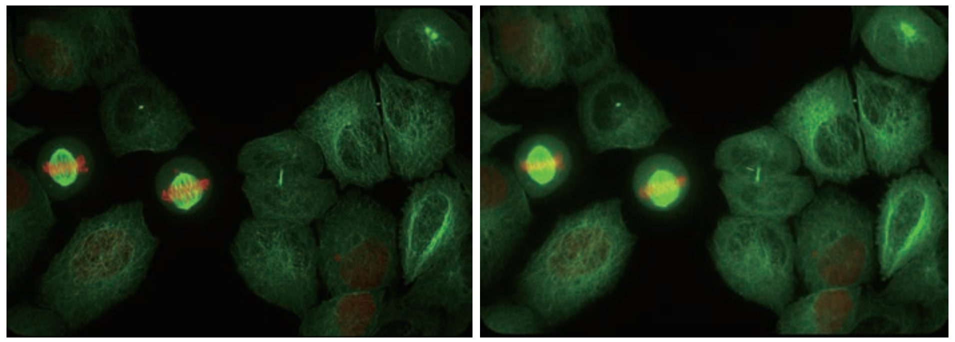
NanoLuc fusion protein ARRB2 and Venus fusion protein V2R are nearby and BRET is occurring.

Data courtesy of Dr.Masataka Yanagawa, Department of Molecular & Cellular Biochemistry Graduate School of Pharmaceutical Science, Tohoku University

Super resolution microscopy

Super resolution microscopy refers to a collection of methods to get a microscope image with higher spatial resolution than diffraction limit.
The super resolution microscopy needs scientific cameras with combination of very low noise and small pixel size, resulting in a higher resolution.

Super resolution images from ORCA-Quest and ORCA-Fusion

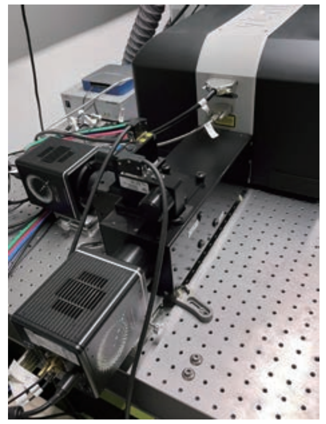


ORCA-Quest
(qCMOS camera, 4.6 μm pixel size)

ORCA-Fusion
(Gen III sCMOS camera, 6.5 μm pixel size)

Data courtesy of Steven Coleman at Visitech international with their VT-iSIM, high speed super resolution live cell imaging system.

Experimental setup with ORCA-Quest



Application and Measurement Examples

Astronomy

Lucky imaging

When observing stars from the ground, the image of the star can be blurred due to atmospheric turbulence therefore substantially reducing the ability to capture clear images.
However, with short exposures and the right atmospheric conditions, you can sometimes capture clear images. For this reason, lucky imaging is a method of acquiring a large number of images and integrating only the clearest ones while aligning them.

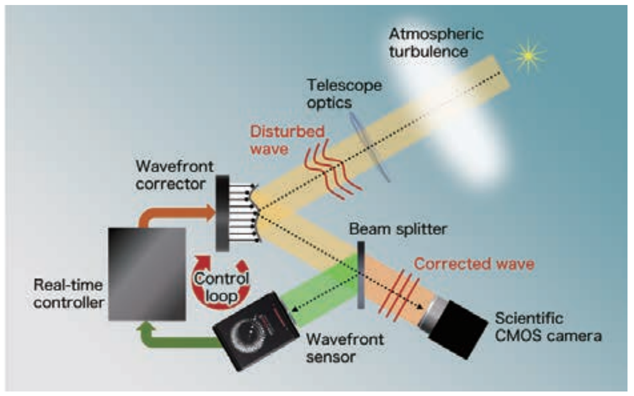
Orion Nebula (Color image with 3 wavelength filters)

Imaging setup

Adaptive optics

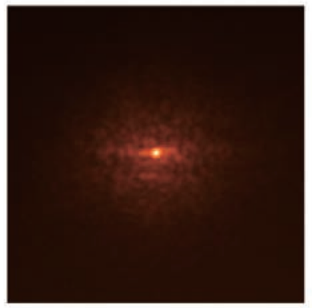
Adaptive optics is a method where systems immediately correct the wavefront of incoming light which is disturbed by atmospheric fluctuations. In order to perform real-time and highly accurate wavefront correction, a camera needs to get images with high speed and high spatial resolution. In addition, the camera also needs high sensitivity because the wavefront correction is performed in a very dark condition where a laser guide star is measured.

Wavefront correction by adaptive optics

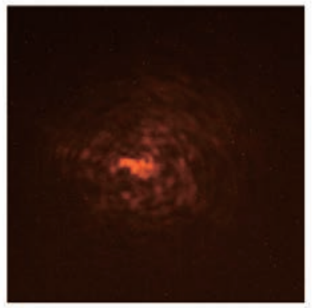


Comparison of adaptive optics

With adaptive optics



Without adaptive optics

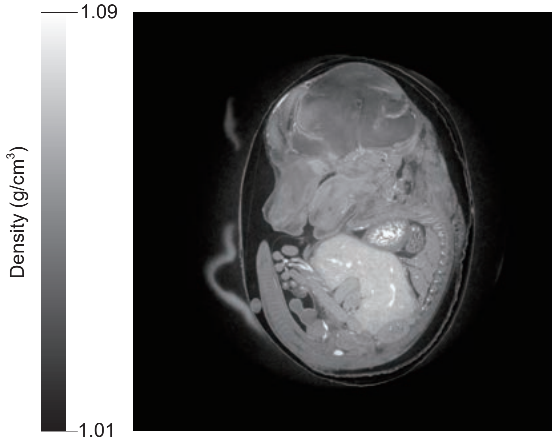


Conditions: wind speed 10 m/s, exposure time 6 seconds in the laboratory
Data courtesy of Kodai Yamamoto, Ph.D., Department of Astronomy, Kyoto University

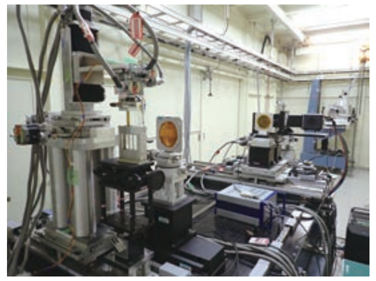
HEP / Synchrotron

For imaging of X-ray or other kinds of high energy particles, a scientific camera coupled with a scintillator is often used. The imaging system must have low noise and high speed to detect momentary phenomena.

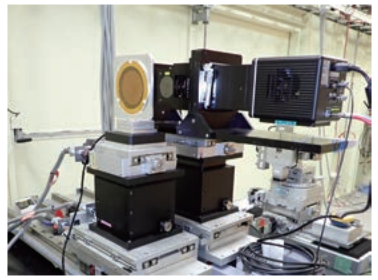
X-ray phase contrast CT image of mouse embryo



Experimental setup



Camera setup

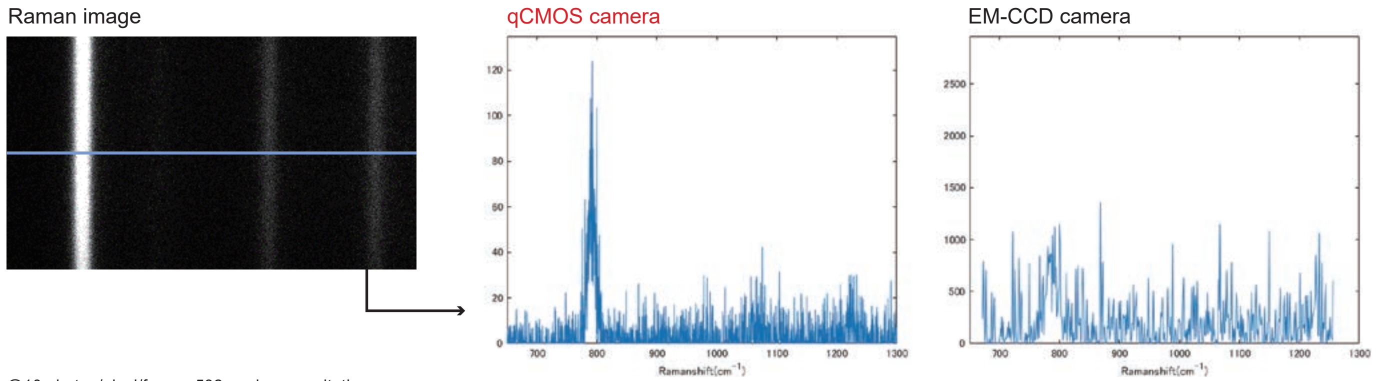


- X-ray phase contrast CT image of a mouse embryo from an ORCA-Quest combined with high resolution X-ray imaging system (M11427)
- Exposure time: 15 ms, Total measurement time: 6.5 min
- Data courtesy of SPring-8 BL20B2 beamline by Dr. Masato Hoshino, Senior Scientist in Japan Synchrotron Radiation Research Institute (JASRI)

Raman spectroscopy

Raman effect is the scattering of light at a wavelength different from that of the incident light, and Raman spectroscopy is a technique for determining the material properties by measuring this wavelength. Raman spectroscopy enables structural analysis at the molecular level, which provides information on chemical bonding, crystallinity, etc.

Raman spectrum (single frame) comparison under condition of equal photon number per pixel in line scan type Raman imaging system



@10 photon/pixel/frame, 532 nm laser excitation
Reference: https://camera.hamamatsu.com/all/en/application_and_case_study/photon_number_resolving_capability.html

Case studies are now available on our website!
https://camera.hamamatsu.com/all/en/application_and_case_study.html

Specification

Product number		C15550-22UP
Imaging device		qCMOS image sensor
Effective number of pixels		4096 (H) × 2304 (V)
Pixel size		4.6 μm (H) × 4.6 μm (V)
Effective area		18.841 mm (H) × 10.598 mm (V)
Quantum efficiency (typ.)		85 % (peak QE)
Full well capacity (typ.)		7000 electrons
Readout noise (typ.)	Standard scan	0.43 electrons (rms), 0.39 electrons (median)
	Ultra quiet scan	0.30 electrons (rms), 0.25 electrons (median)
Dynamic range (typ.) *1		23 000: 1 (rms), 28 000: 1 (median)
Dark signal non-uniformity (DSNU) (typ.) *2		0.06 electrons
Photoresponse non-uniformity (PRNU) (typ.) *2*3		<0.1 %
Linearity error	EMVA 1288 standard (typ.)	0.5 %

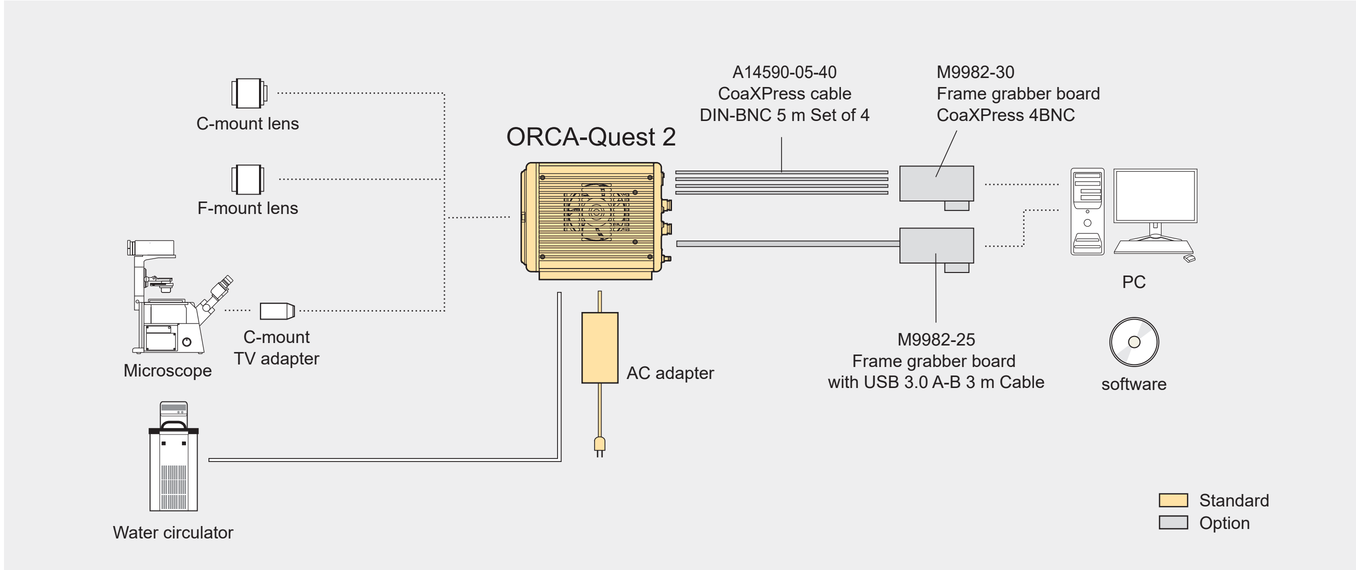
Cooling	Sensor temperature	Dark current (typ.)
Forced-air cooled (Ambient temperature: +25 °C)	−20 °C	0.016 electrons/pixels/s
Water cooled (Water temperature: +25 °C) *4	−20 °C	0.016 electrons/pixels/s
Water cooled [max cooling (Water temperature: +20 °C, Ambient temperature: +20 °C)] *4	−35 °C (typ.)	0.006 electrons/pixels/s

At Normal area readout, Photon number resolving (PNR), and Raw data output (Raw) mode*5		
Readout mode		Full resolution, Digital binning (2×2, 4×4), Sub-array
Frame rate at full resolution	Standard scan *6	120 frames/s (CoaXPress), 17.6 frames/s (USB)
	Ultra quiet scan, PNR, Raw	25.4 frames/s (CoaXPress), 17.6 frames/s (USB)
Exposure time	Standard scan *6	7.2 μs to 1800 s
	Ultra quiet scan, PNR, Raw	33.9 μs to 1800 s *7
Trigger input	External trigger input mode	Edge / Global reset edge / Level / Global reset level / Sync readout / Start
	Software trigger	Edge / Global reset edge / Start
	Trigger delay function	0 s to 10 s in 1 μs steps
At Lightsheet readout (Patented) *8*9		
Readout mode		Full resolution, Sub-array
Readout direction		Forward readout / Backward readout / Bidirectional readout / Reverse bidirectional readout
Row interval time		7.2 μs to 237.6 μs
Exposure time		7.2 μs to 273.7 ms
Trigger input	External trigger input mode	Edge / Start
	Software trigger	Edge / Start
	Trigger delay function	0 s to 10 s in 1 μs steps

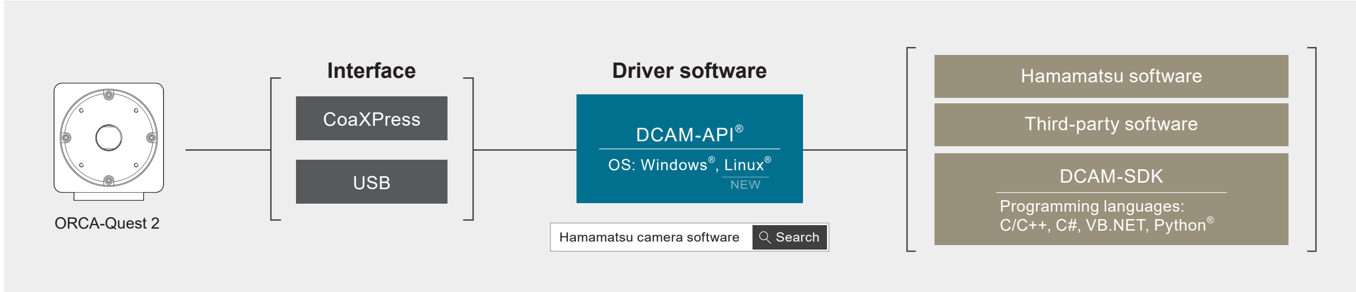
Trigger output		Global exposure timing output / Any-row exposure timing output / Trigger ready output / 3 programmable timing outputs / High output / Low output
Master pulse	Pulse mode	Free running / Start trigger / Burst
	Pulse interval	5 μs to 10 s in 1 μs step
	Burst count	1 to 65 535
Digital output		16 bit / 12 bit / 8 bit
Image processing function		Defect pixel correction (ON or OFF, hot pixel correction 3 steps)
Emulation mode		Available (ORCA-Quest, ORCA-Fusion)
Interface		USB 3.1 Gen 1, CoaXPress (Quad CXP-6)
Trigger input connector		SMA
Trigger output connector		SMA
Lens mount		C-mount *10
Power supply		AC100 V to AC240 V, 50 Hz/60 Hz
Power consumption		Approx. 155 VA
Ambient operating temperature		0 °C to +40 °C
Ambient operating humidity		30 % to 80 % (With no condensation)
Ambient storage temperature		−10 °C to +50 °C
Ambient storage humidity		90 % Max. (With no condensation)

*1: Calculated from the ratio of the full well capacity and the readout noise in Ultra quiet scan
*2: In Ultra quiet scan
*3: At 3500 electrons, the center 1500 × 1500 area of the image sensor, 1000 times integration
*4: Water volume is 0.46 L/m.
*5: PNR mode and Raw mode can be switched via DCAM configurator. The PNR mode is selected by default.
*6: Normal area readout mode only
*7: For both global reset edge trigger and global reset level trigger, the minimum exposure time is 67.8 μs.
*8: Software such as HCImage is required. For details, please contact your local Hamamatsu representative or distributor.
*9: For more patent information, please refer to our website. https://www.hamamatsu.com/all/en/product/cameras/cmos-cameras/lightsheet-readout-mode.html
*10: A product for F-mount (C15550-22UP01) is also available. If you wish, please contact your local Hamamatsu representative or distributor. F-mount has a light leakage due to its structure and it might affect your measurements especially with longer exposure time.

System Configuration



Software and Interface

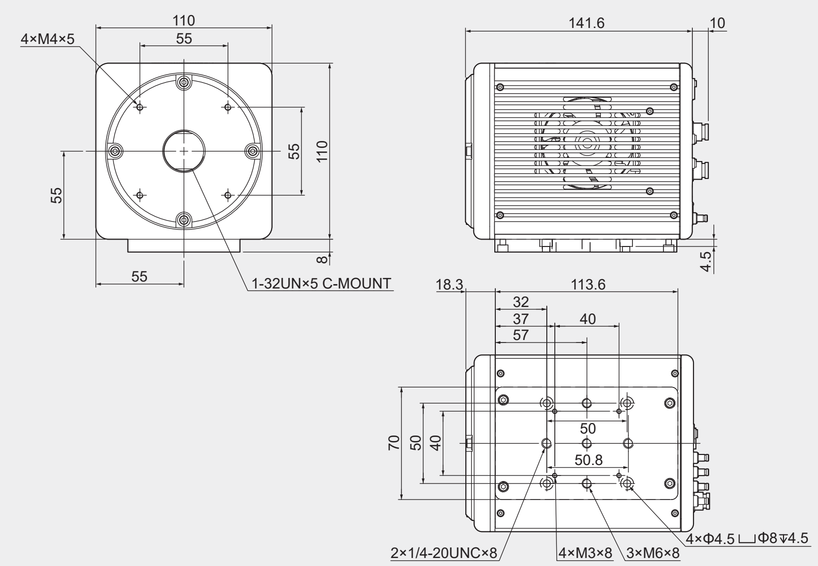


Option

Product number	Product name
M9982-30	Frame grabber board CoaXPress 4BNC
A14590-05-40	CoaXPress cable DIN-BNC 5 m Set of 4
A14590-10-40	CoaXPress cable DIN-BNC 10 m Set of 4
M9982-25	Frame grabber board with USB 3.0 A-B 3 m Cable
A12106-05	External trigger cable SMA-BNC 5 m
A12107-05	External trigger cable SMA-SMA 5 m

Dimensional Outlines (Unit: mm)

Camera (Approx. 3.8 kg)



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