IGNITING QUESTIONS

DETECTING ANSWERS

HAMAMATSU

PHOTON IS OUR BUSINESS

"Scientists have become the bearers of the torch of discovery in our quest for knowledge."

—STEPHEN HAWKING

Start your adventure.

Introducing the new qCMOS®

ORCA®-Quest

Photon Number Resolving

> “Light is possibility itself.”
>
> — TERUO HIRUMA
> PHOTONICS VISIONARY AND FORMER PRESIDENT OF HAMAMATSU PHOTONICS

LOW READOUT NOISE
0.27 ELECTRONS RMS
ULTRA-QUIET SCAN

HIGH QE
90 % @475 nm
BACK-ILLUMINATED qCMOS

HIGH RESOLUTION
4096 × 2304
9.4 MEGAPIXELS

HIGH SPEED
120 FRAMES/S
@4096 × 2304 PIXELS (16 BIT)

ORCA-Quest

Photon Number Resolving

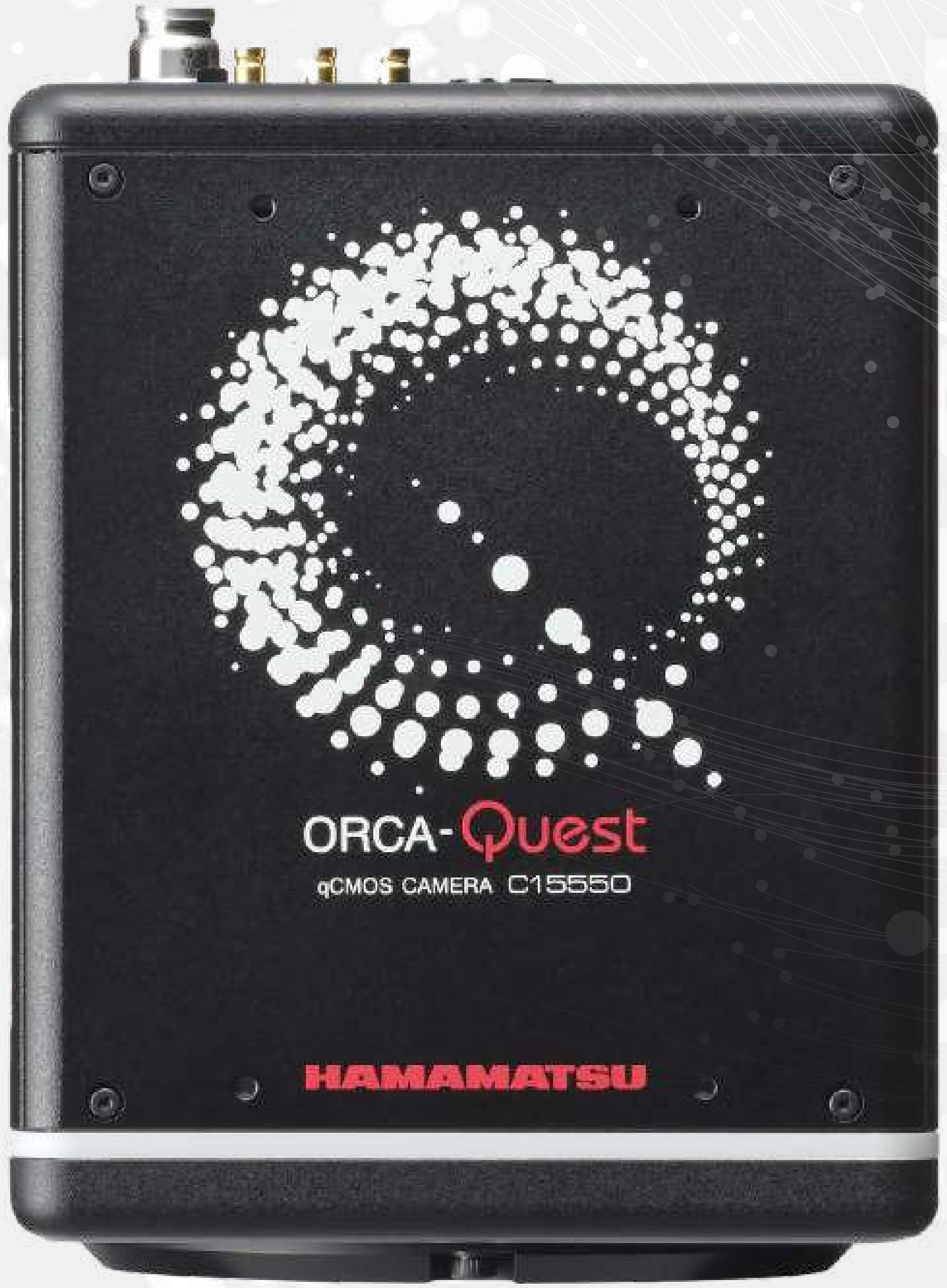
Groundbreaking in concept and unprecedented in performance.

The ORCA-Quest quantitative CMOS (qCMOS) camera with Photon Number Resolving functionality is the leap in scientific camera evolution that transforms imaging into imagining.

With ultra-quiet, highly-refined electronics, this camera is more than an image capture device; it is a precision instrument that unlocks the ability to investigate new photonic questions because it offers the quality and quantitative performance to detect meaningful data previously lost in the noise.

Our journey to create the ORCA-Quest is only the prologue to many epic adventures. These stories are the tales of scientific exploration done with a new and powerful tool.

Let your discovery begin...



Photon Number Resolving

“Measure what can be measured. And make measurable what cannot be measured.”

—GALILEO GALILEI

IGNITING QUESTIONS DETECTING ANSWERS

Photon Number Resolving Mode

From philosophy to physics, biology to art, light is both essential and mysterious. At the fundamental level, understanding photons and manipulating light both informs and advances scientific discovery. Until now, there has never been a 2D detector capable of measuring individual photons.

So, what does it mean that Hamamatsu's ORCA-Quest has photon number resolving capabilities?

First, let's be clear, as with any digital imaging device what is being detected and measured are photoelectrons. And resolving individual photo(electro)ns has primarily been the domain of point detectors such as photomultiplier tubes (PMTs) and Single-photon Avalanche Diode (SPADs). Photon counting is a measurement technique that relies on the properties of these detectors to indicate whether a photon (or two) has been detected with some level of certainty. But they cannot "count" photons much beyond the threshold of a binary yes or no.

In Photon Number Resolving Mode, the ORCA-Quest outputs actual counts of photoelectrons per pixel up to a max of 200 photons.

Single photon sensitivity in a camera is not achieved through a single specification. This is achieved through careful sensor and camera design that reduces camera noise low enough to be able to discriminate single photons within a pixel and manages pixel to pixel variability to expect each pixel will behave similarly in space and time. While low read noise is essential, it is the combination of low read noise, low dark current, high QE, sensor uniformity, advanced pixel level dark offset and gain calibrations and on-board FPGA processing to convert small voltage changes into photoelectron counts with sufficient statistical certainty that enables photon number resolving, creating a camera that is truly quantitative.

Photon Number Resolving Mode

What can be achieved with the ORCA-Quest and Photon Number Resolving Mode?

New technologies bring the promise of new discoveries. But it takes time to understand, develop and appreciate the potential. We imagine that the ORCA-Quest will enable previously unexplored paths of discovery in the areas of quantum photonics, astronomy, spectroscopy, live cell fluorescent imaging, bioluminescence and all the “omics.” The beauty of the ORCA-Quest is that it was created out of the spirit of adventure to enable discovery. It is an instrument designed for new directions in exploration.

Quantitative CMOS (qCMOS) is more than Photon Number Resolving

Let’s imagine a perfect camera. We would define it as one that had no read noise or dark current and could detect every incident photon. Even in this theoretical ideal, there is still an element of noise and that is shot noise; the variability in the photon flux of the signal itself.

In a perfect camera with zero noise and 100 % quantum efficiency, the discrete nature of photons can be detected, because photon shot noise is the only fluctuating component of the signal. Since the light source emits photons randomly and independently of each other, the photon flux exhibits a Poisson probability distribution. Poisson distributions are well described (for example see Chapter 3, ORCA-Quest Photon Number Resolving Camera Technology White Paper) but the important take-aways are that: a) they present probability for discrete values, b) there is zero probability for observing less than zero events and c) the noise, or standard deviation, is equal to the square root of the average photon number. In imaging, this means that you can never have negative intensity and that the signal noise, or shot noise, is the square root of the photon number.

A perfect camera does not exist, so when the electronic Gaussian noise of a camera is added to the Poisson photon shot noise, the probability distribution for observing a given number of photons is confounded by the uncertainty of the camera, effectively blurring the probability distribution. This is shown graphically in Fig. 1-1.

Drawing on an understanding of the nature of noise and probability distributions, if the requirement is to correctly classify photoelectron “counts” for more than 90 % of the photodetection events, a readout noise of 0.3 electrons rms or less is required (see Chapter 3, ORCA-Quest Photon Number Resolving Camera Technology White Paper). Until recently such low read noise was unattainable, but advances in sensor manufacturing, including ultra-micro semiconductor design rules and sophisticated camera calibrations, now allow for such precision.

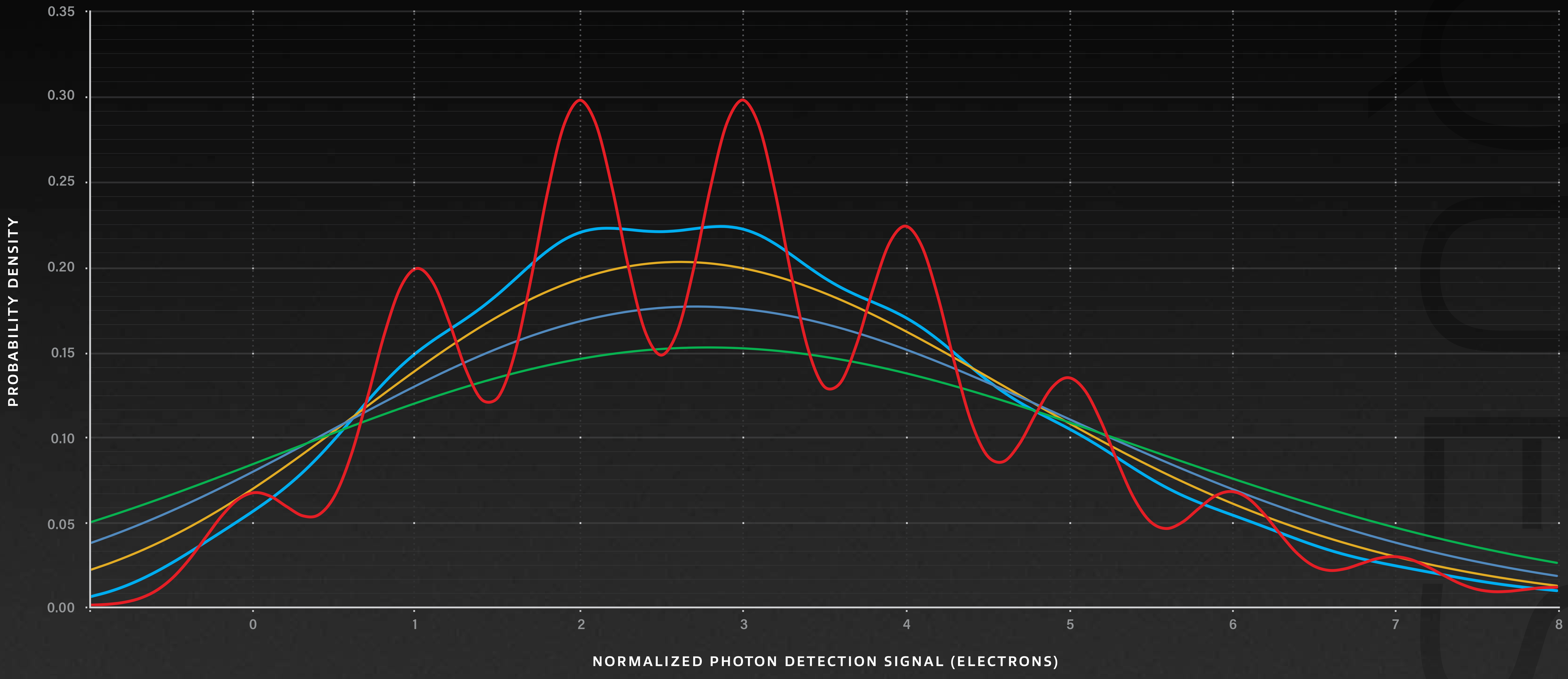


Fig. 1-1 The effect of camera noise on photon number resolving

All five curves plot the probability distribution for a theoretical signal with a mean of three photoelectrons. The x-axis is the normalized signal in photoelectrons and the y-axis is the probability for a discrete photon number. In red is the calculated distribution for the ORCA-Quest with 0.27 e- rms All other curves are calculated with increasing read noise: 0.5, 1.0, 1.5 and 2.0 e- rms As read noise increases, the distribution becomes blurred and there is no distinction between discrete photoelectron numbers. Photon number resolving is impossible even at 0.5 e- rms

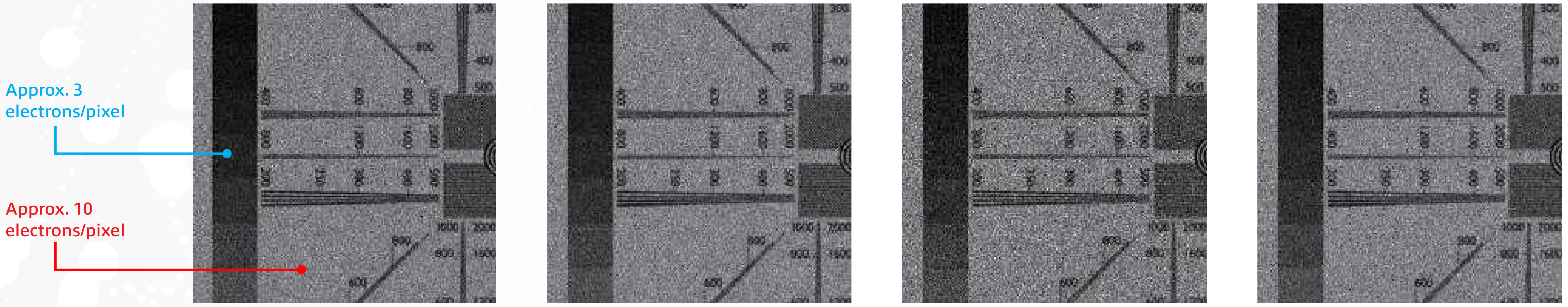
Photon Number Resolving Mode

CONTINUED

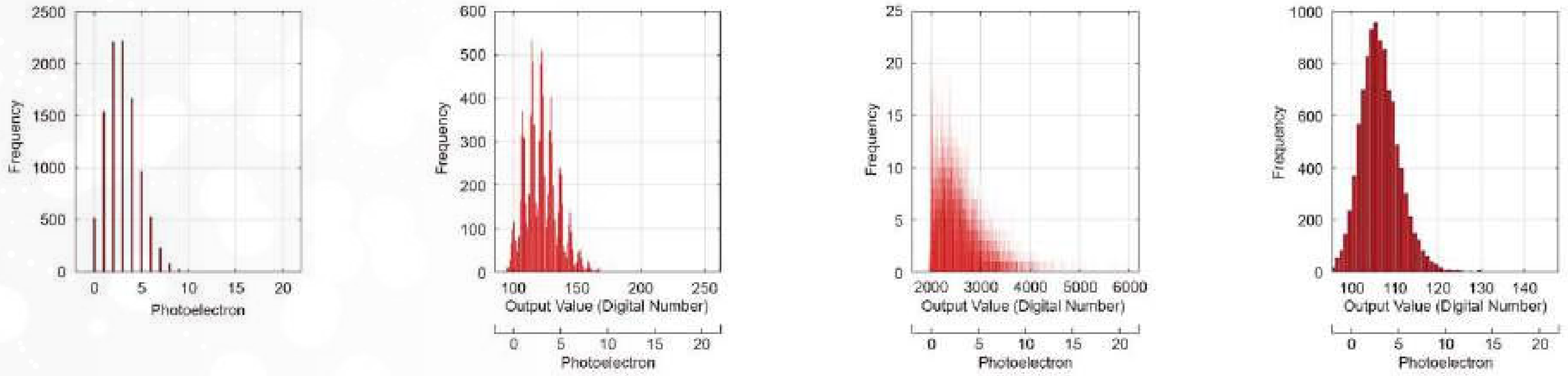
Even so, the gap between theory and practice needed to be bridged. Hamamatsu dedicated significant engineering effort and partnered with the premiere manufacturer of CMOS sensors to create the world's first quantitative CMOS (qCMOS), with a read noise of 0.27 e- rms.

While Photon Number Resolving Mode is useful in extreme low light scenarios, the engineering that enables this advancement is broadly beneficial in most scientific applications especially for discovery that relies on post-acquisition computational or statistical methods. As with any type of image analysis, the higher the data quality or information content at the start, the better the outcome after processing. The low noise and high uniformity of the image data from the ORCA-Quest, in all modes, enables quantitative imaging over a wide range of input photon level, speeds, wavelengths and delivers superb results from post-processing algorithms.

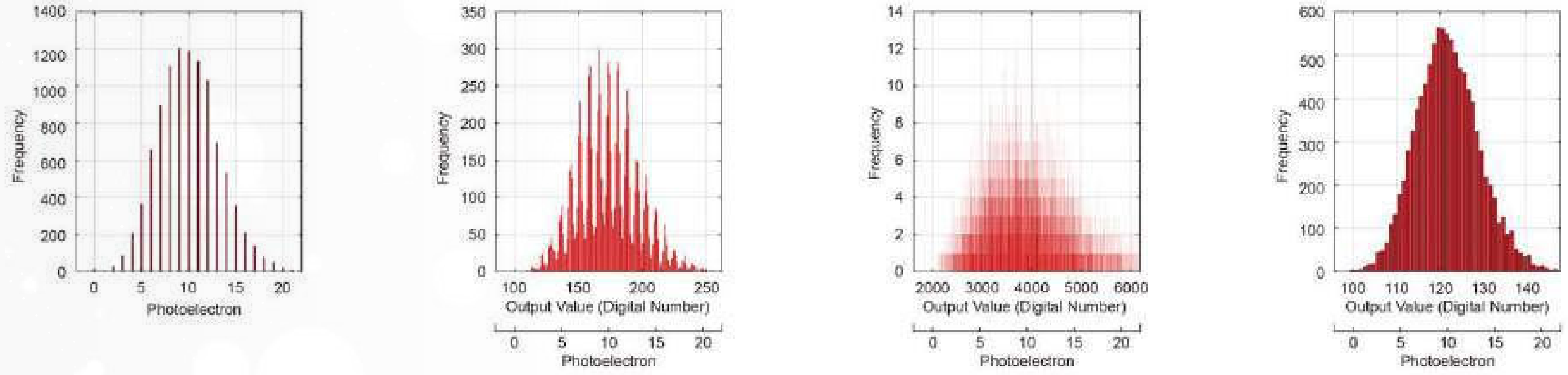
ORCA®-Quest	ORCA®-Quest	EM-CCD camera	Gen II sCMOS camera
Photon Number Resolving	Ultra-Quiet Scan		



Average number of photoelectrons generated per pixel: 3 electrons



Average number of photoelectrons generated per pixel: 10 electrons



"The real voyage of discovery consists not in seeking new landscapes but in having new eyes."

—MARCEL PROUST

IGNITING QUESTIONS DETECTING ANSWERS

See what's been hidden in the noise

For as long as scientific digital cameras have been available, SNR has been a benchmark of performance. Calculated from the input photon level and camera noise specification, a high SNR typically provides better quality images, especially for intensity quantification and post-acquisition computational analysis.

When Hamamatsu released our first scientific CMOS, we took traditional SNR curves and made them relative to a perfect camera. This simple transformation to relative SNR (rSNR) provided a clear window into SNR performance at low light (< 10 average input photons) and the specific impact of read noise, QE and EM-CCD excess noise factor on SNR. rSNR makes it easy to see that read noise is critical in the lowest light conditions, that QE defines the upper limit of SNR and that excess noise from an EM-CCD effectively reduces it's QE by half.

Fig. 2-1 shows the rSNR curve for the ORCA-Quest in ultra-quiet and standard modes and compares that to other cameras with real-world specifications. It is important to note that this curve is adjusted for pixel size so that all pixels are optically equivalent. If pixel size is not considered the total area of photon detection will dominate and skew the results.

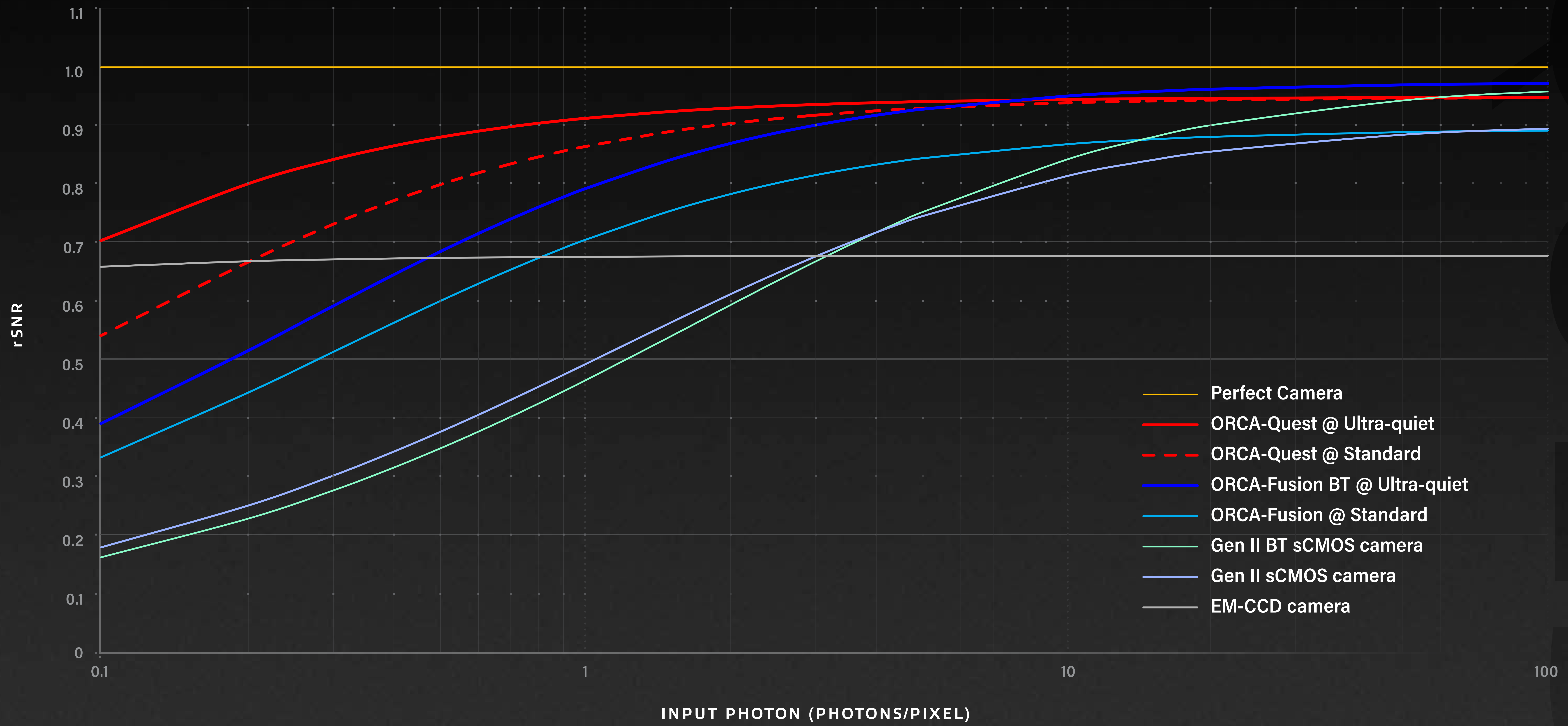


Fig. 2-1 Relative SNR (Relative to perfect camera)

When photons are scarce either because there are few to detect or imaging speeds or conditions limit capture, read noise defines the lower-limit boundary of detectability. Across multiple chip generations, CMOS has been approaching the realm of EM-CCD sensitivity at less than 10 photons. The ORCA-Quest can now compete with EM-CCD-level SNR in the lowest light levels while also providing a larger field of view, faster frame rates, and higher resolution in both pixel number and MTF. (Specification used as e- r.m.s. and QE %: ORCA-Quest 0.27, 90 % (ultra-quiet), 0.43, 90 % (standard); ORCA-Fusion BT 0.7, 95 % (ultra-quiet); ORCA-Fusion 0.7, 80 % (standard); Gen II sCMOS 1.4, 82 %, EM-CCD 0.1, 92 %)

See what's been hidden in the noise

CONTINUED

The Devil is in the Details: The subtle aspects of camera noise and data quality.

Read noise is just one component of the electronic noise in a camera that can degrade SNR and image quality. To get a complete picture of camera performance, the following specifications are also relevant: read noise distribution, dark current, gain and offset non-uniformity, etaloning and image modulation transfer function (MTF).

Each one of these topics could be a full lecture on camera electronics, but to keep this simple and meaningful, the technical explanation will be just enough to appreciate the implications on actual performance.

Eliminating Noisy Pixels.

Simplistically, read noise is pixel variation in the conversion of a charge to a digital signal. Each pixel's photoelectron charge must be detected, converted to voltage, amplified and digitized. Each of these steps has error associated with it. Read noise is specified as electrons rms to capture in one number the most meaningful specification. But in a camera with 9.4 megapixels, the pixel to pixel variation in read noise across the sensor and/or in a single pixel over time, can impact image quality and data analysis. In fact, variability in CMOS sensors was the Achilles heel of this technology for decades and CCDs were the chosen sensor because of their dependable uniformity. With the release of the first sCMOS cameras, uniformity became good enough but it was not until the release of the Gen III, ORCA-Fusion series of cameras that CMOS uniformity approached CCD-like quality. The ORCA-Quest pushes that boundary even further and, as can be seen in Fig. 2-2, has a very narrow read noise distribution, minimizing the salt and pepper visual effect of noisy pixels that can also wreak havoc on computational techniques such as precision localization super resolution.

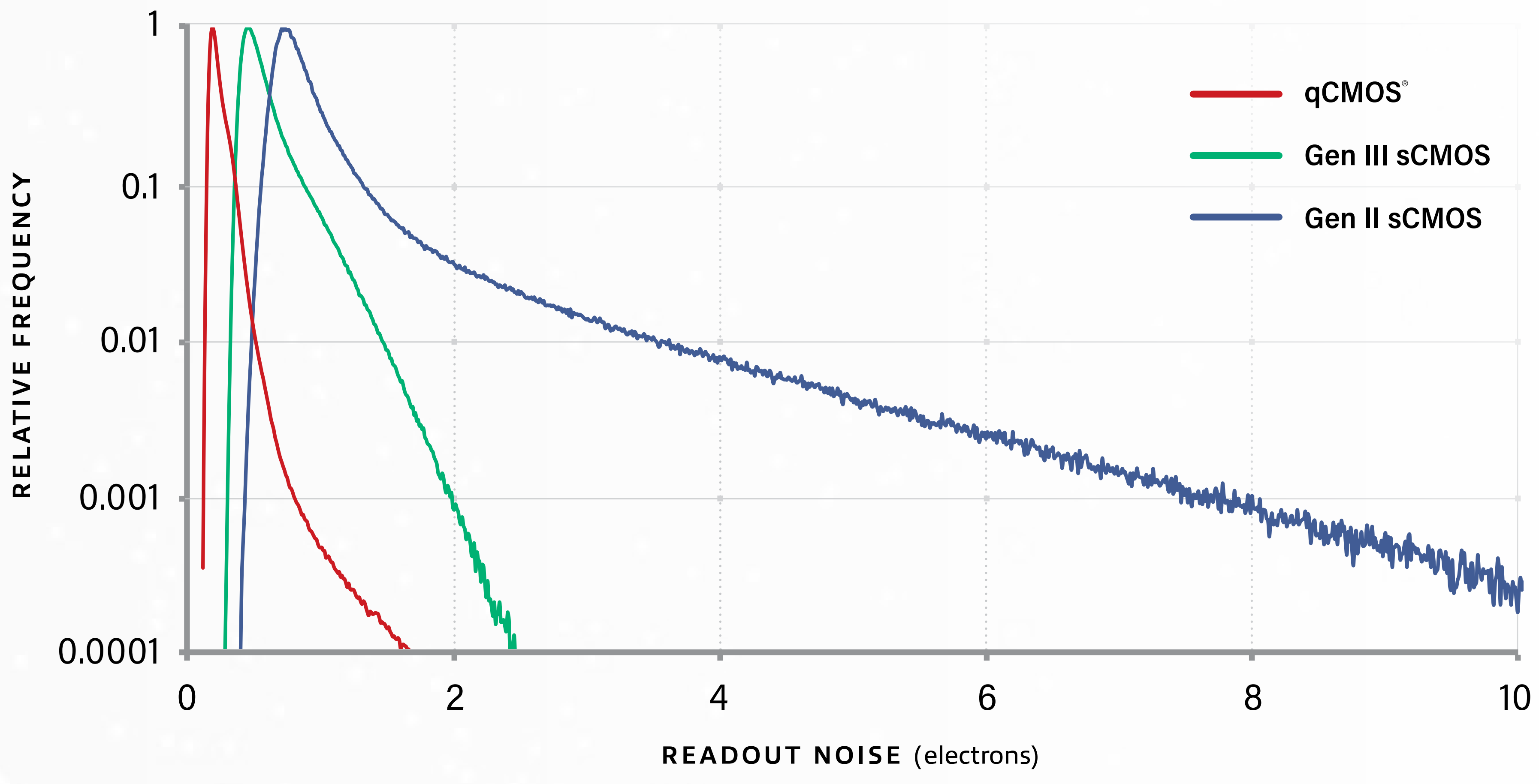


Fig. 2-2

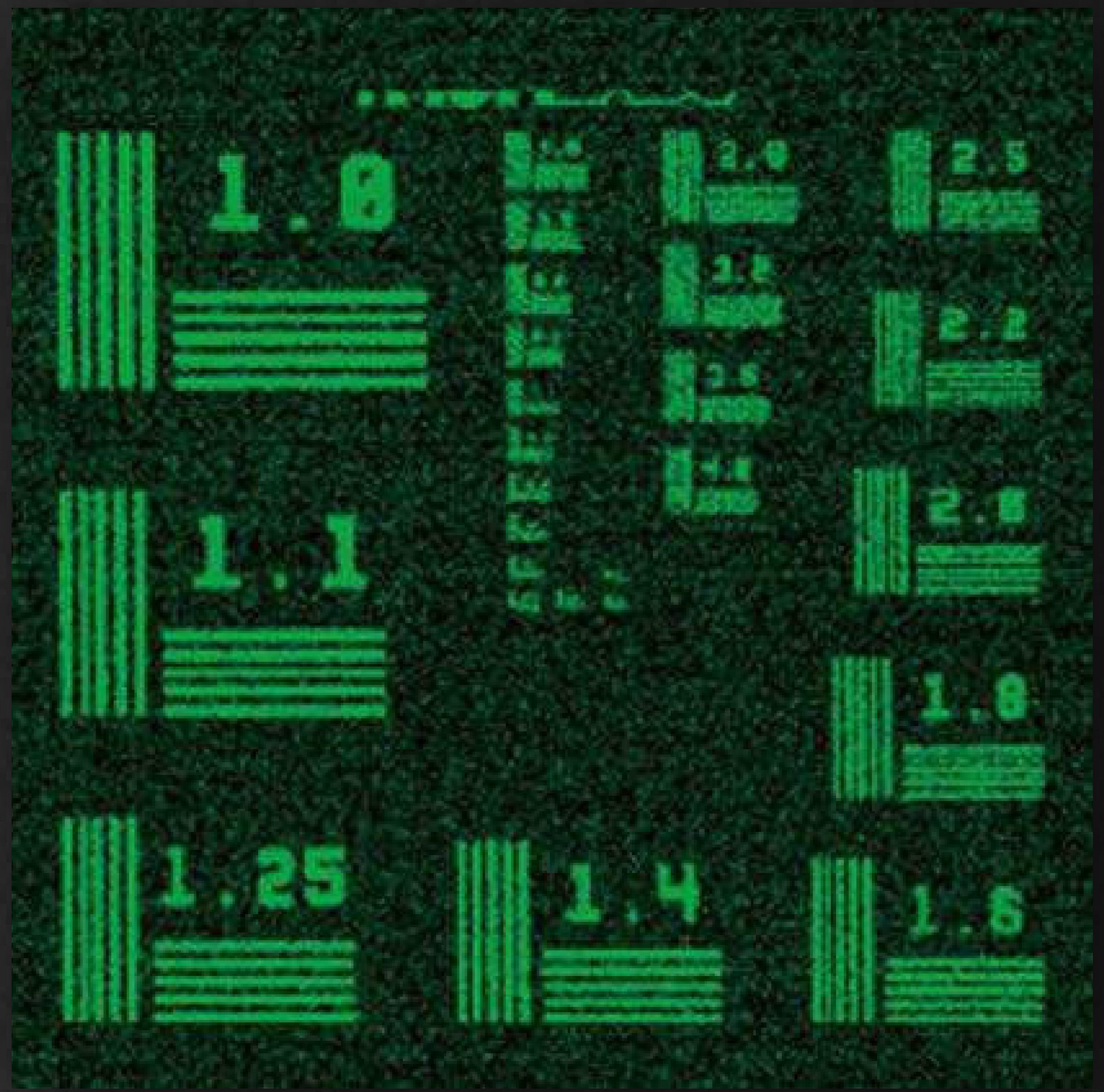
See what's been hidden in the noise

CONTINUED

Staying Dark in the Heat

An unavoidable issue with using silicon for sensing photons is that as the sensor heats up, electrons can be generated in the detector that are indistinguishable from electrons generated from photons. There is a known amount of this dark current for each sensor that depends on the particular chemistry of the silicon substrate and is expressed as electrons/pixel/second. This value can be reduced by cooling the sensor. But cooling is a complex part of camera design and the goal of sensor manufactures is to create a detector with very little dark current even with little or no cooling. This is yet another breakthrough for the ORCA-Quest. With 0.006 e-/p/s dark current at -35 °C, the contribution of dark noise to the overall noise is very small and is low enough for exposures beyond a few seconds. This is yet another area of unexplored terrain for CMOS imaging and the ORCA-Quest, by staying dark, can light the way.

ORCA®-Quest



Gen II sCMOS camera

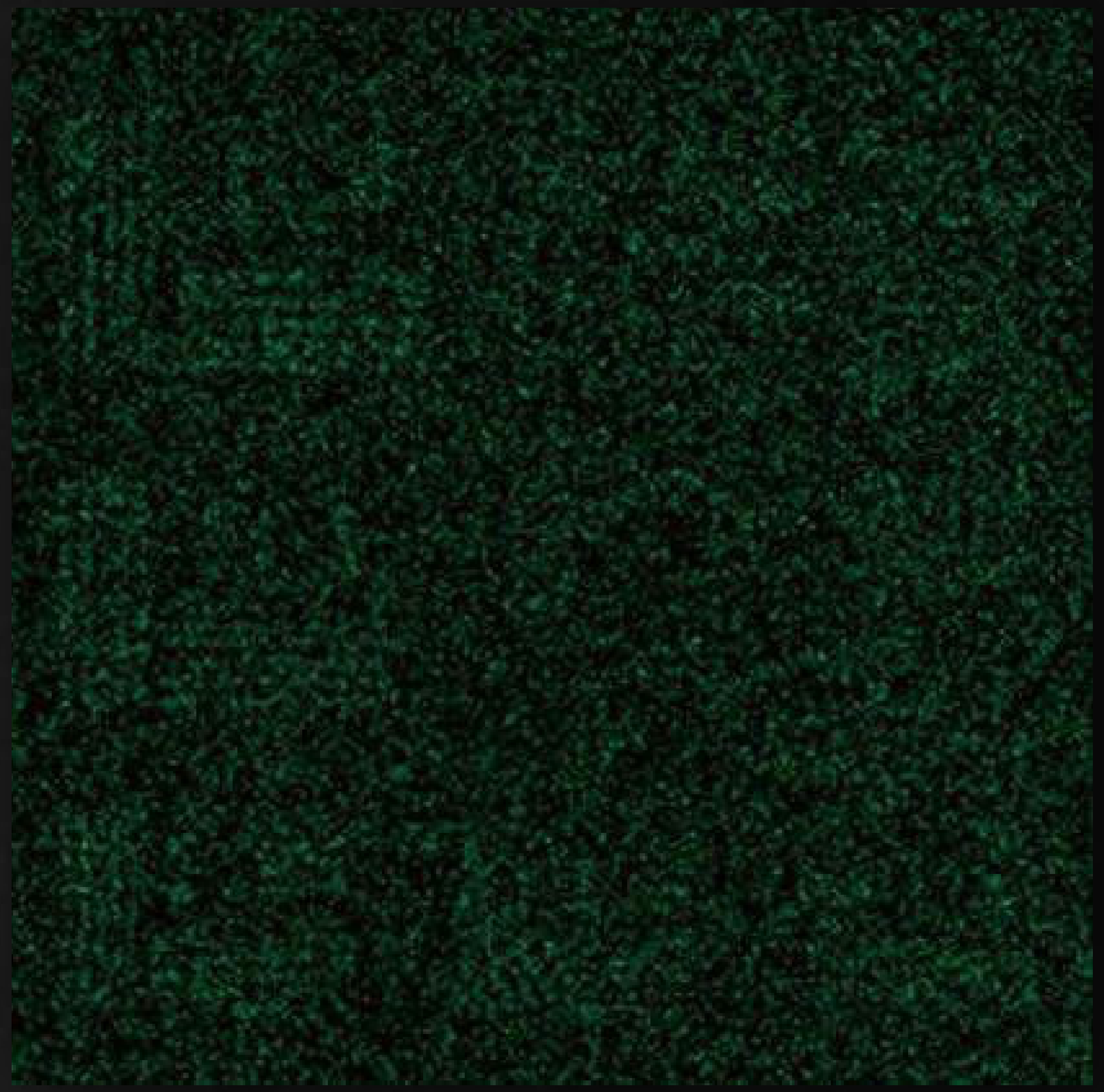


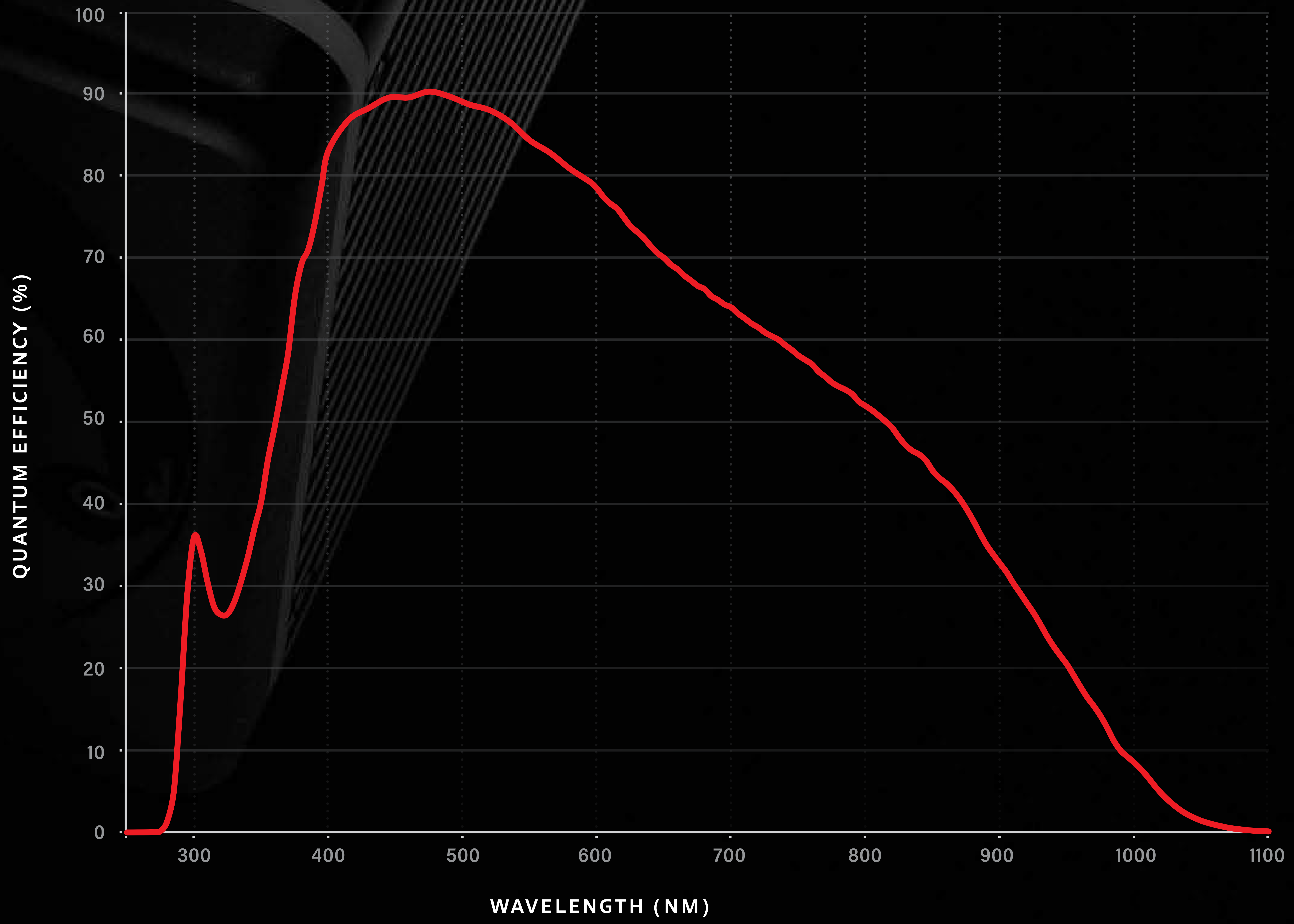
Fig. 2-3 Image quality comparison at long exposure time (pseudo-color)

Exposure time: 15 min (10 s x 90 times integration)

"The most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects we have not yet imagined."

—JOHN N. BAHCALL

IGNITING QUESTIONS DETECTING ANSWERS


100
90
80
70
60
50
40
30
20
10
0
QUANTUM EFFICIENCY (%)
300
400
500
600
700
800
900
1000
1100
WAVELENGTH (NM)


ORCA-Quest
qCMOS CAMERA C15550
HAMAMATSU

Fig. 3-1

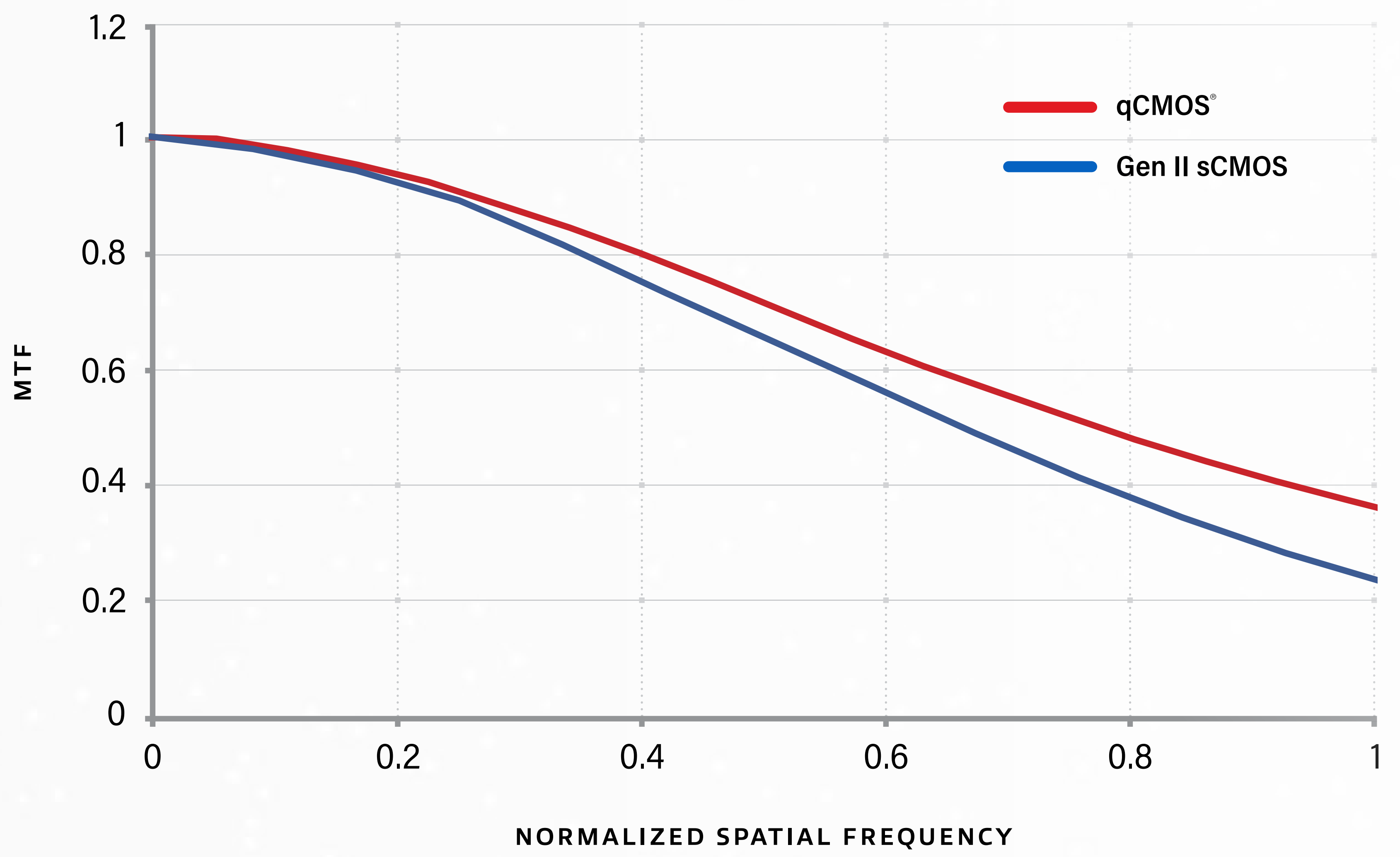
Making Back-Thinned Better

Back-thinning CCDs for enhanced QE has been done for decades and EM-CCDs are an example of back-thinned technology becoming commonplace. There are two tradeoffs around back-thinning that are often underestimated: etaloning and impaired resolution as measured by modulation transfer function. As with any transformative new product, clever new features take the headlines. But often it is the minimization of age-old nagging issues that frees up the technology for greatness.

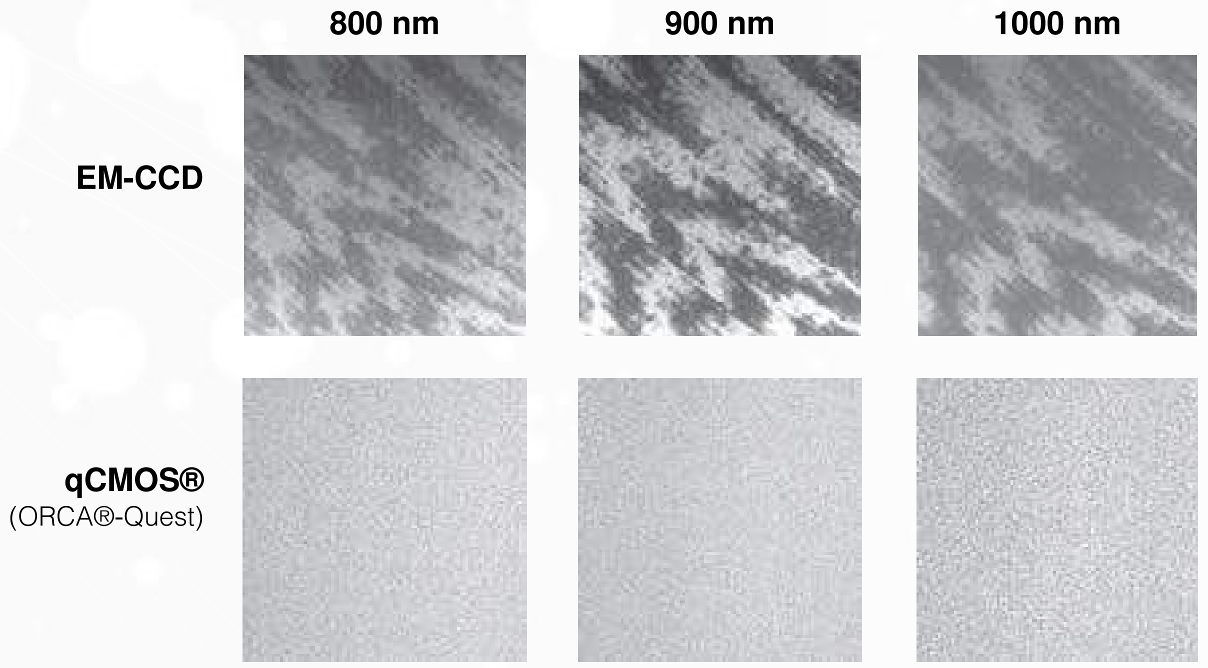
As can be seen in Fig. 3-1, at wavelengths above 700 nm, light can reflect within the silicon causing interference patterns that interfere with quantitative measurements. The ORCA-Quest is created using the most advanced sensor manufacturing techniques; the improved quality of the images from the ORCA-Quest speak for themselves.

Resolution is typically considered as the overall number of pixels and pixel size. But pixel structure can also play a role in functional resolution. Every pixel is expected to collect light only from an optically specified area. But if the incoming photons from that area create change in an adjacent pixel, there is then crosstalk among the pixel and deterioration of resolution. By creating a deep trench isolation structure in the pixel design of the ORCA-Quest, crosstalk is minimized. This improvement is measured by calculating how many patterned lines of contrasting light and dark can be resolved in a given area. Compared to back illuminated sCMOS the ORCA-Quest shows noticeable improvement in MTF which will produce greater sharpness in images at all magnifications.

Measurement results of MTF



Etaloning



Etaloning is a phenomenon that occurs when the incident light interferes with the reflected light from the back surface in the silicon and causes alternately high and low sensitivity. In the case of an EM-CCD camera, it appears as a stripe image even with uniform input light when the back-side illuminated sensor is used with mono infrared wavelength light. Using the latest CMOS image sensor technologies, the qCMOS camera is etaloning-desensitized.

“Science progresses best when observations force us to alter our preconceptions.”

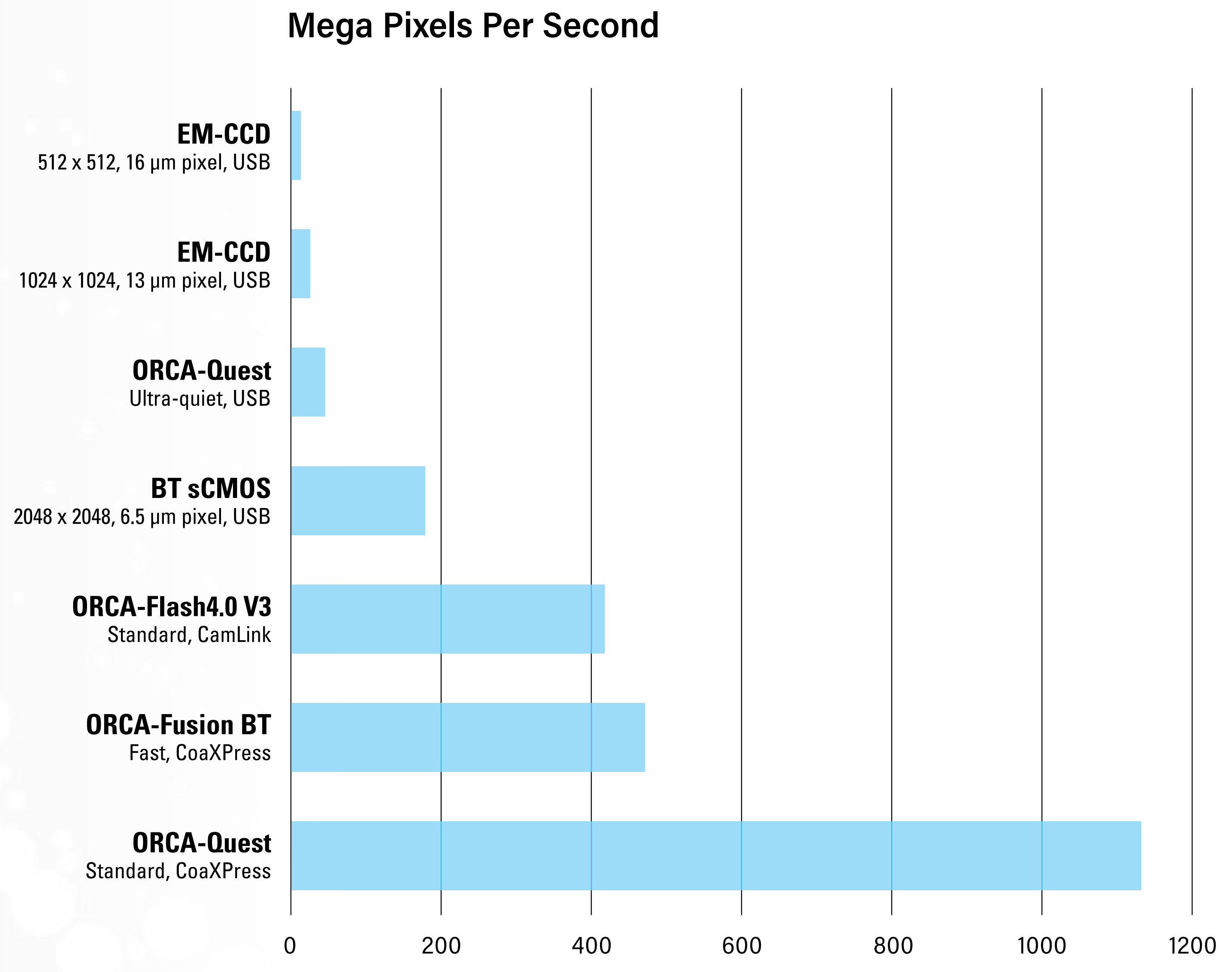
—VERA RUBIN

IGNITING QUESTIONS DETECTING ANSWERS

Practically Pixel Perfect

There is no perfect camera, but the ORCA-Quest gets as close to what might be the ideal scientific camera. In addition to having all the right numbers when it comes to noise and QE, the ORCA-Quest delivers on pixel size, array size and speed as well. It is truly the tool for any scientific adventure. The 4.6 μm pixel size is neither too big nor too small. It is ideally matched to Nyquist requirements at 20x and 40x magnification but is adaptable either through binning or optical techniques to be just right for most microscopy applications.

What particularly stands out about the ORCA-Quest is the speed at which all 9.4 megapixels can be read out. In standard scan mode, the ORCA-Quest runs at 1132 megapixels per second (or 120 frames per second) while maintaining read noise at 0.43 e- r.m.s. This pixel rate is over 6x faster but with less than half the read noise of Gen II BT sCMOS camera. Even in ultra-quiet mode, the ORCA-Quest offers 47.2 megapixels per second while the fastest EM-CCD is only 27.2 megapixel per second. The speed of the ORCA-Quest is achieved all while also having impressive spatial resolution, an excellent MTF, minimal etaloning and high SNR even with few photons. No other camera delivers the versatility of speed and sensitivity that the ORCA-Quest provides.

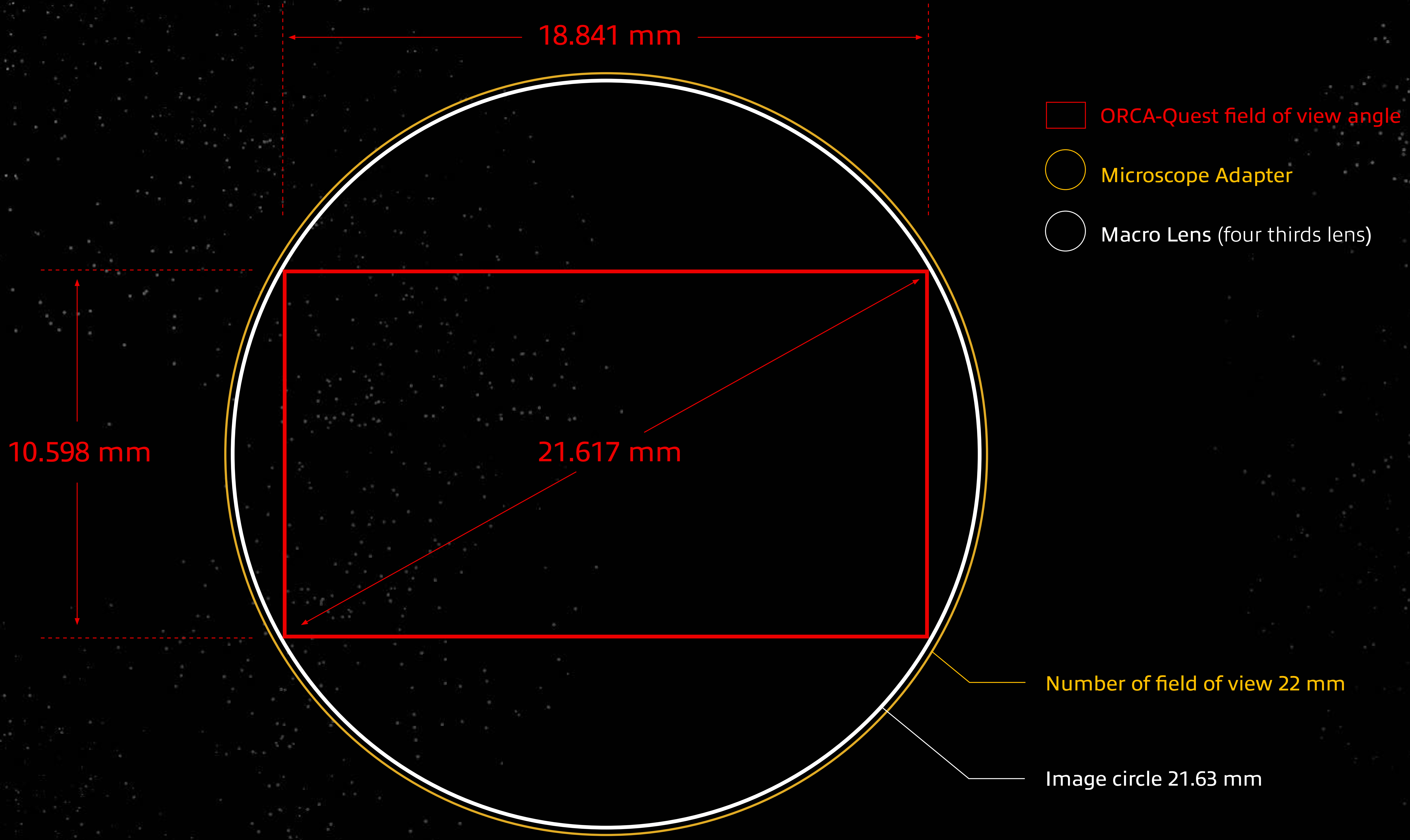


FRAMES PER SECOND (FPS)

ACTIVE PIXEL AREA		AREA READOUT MODE			LIGHTSHEET READOUT MODE	
Columns (X) x Rows (Y)		Standard scan		Ultra-quiet scan	Standard scan	
X (pixels)	Y (pixels)	CoaXPress	USB 3.1 Gen I (16 bit)	CoaXPress and USB 3.1 Gen I (16 bit)	CoaXPress	USB 3.1 Gen I (16 bit)
4096	2304	120	17.6	5.00	119	17.6
4096	2048	134	19.9	5.62	134	19.9
4096	1024	268	39.6	11.1	267	39.6
4096	512	532	78.9	22.1	526	78.9
4096	256	1044	156	43.5	1021	156
4096	128	2012	304	83.8	1929	304
4096	8	15 432	2893	643	11 574	2893
4096	4	19 841	4084	826	13 888	3968

TYPICAL FPS WITH 2×2 BINNING

ACTIVE PIXEL AREA		AREA READOUT MODE			LIGHTSHEET READOUT MODE
Columns (X) x Rows (Y)		Standard scan		Ultra-quiet scan	Standard scan
X (pixels)	Y (pixels)	CoaXPress	USB 3.1 Gen I (16 bit)	CoaXPress and USB 3.1 Gen I (16 bit)	CoaXPress and USB 3.1 Gen I (16 bit)
2048	1152	120	35.3	5.00	N/A
2048	1024	134	39.8	5.62	N/A
2048	512	268	79.3	11.1	N/A
2048	256	532	157	22.1	N/A
2048	128	1044	312	43.5	N/A
2048	64	2012	609	83.8	N/A
2048	4	15 432	5787	643	N/A
2048	2	19 841	8169	826	N/A


18.841 mm
10.598 mm
21.617 mm
ORCA-Quest field of view angle
Microscope Adapter
Macro Lens (four thirds lens)
Number of field of view 22 mm
Image circle 21.63 mm

“An experiment is a question which science poses to nature and a measurement is the recording of nature’s answer.”

—MAX PLANCK

IGNITING QUESTIONS

DETECTING ANSWERS

Software Support

Without robust software a camera is an instrument of frustration not exploration. The ORCA-Quest qCMOS camera is fully supported in Hamamatsu's HCImage and HiPic software. In addition, Hamamatsu provides numerous software tools to help investigators develop software within their own lab environment.

At the core of running all Hamamatsu's cameras is our DCAM-API. Robust, stable and compatible with all Hamamatsu Cameras and interfaces, this underlying layer of software is needed and freely provided with any front-end, user-interface software that runs Hamamatsu Cameras.

To access controls for developing a custom user interface that integrates with DCAM-API, developers must download the DCAM-API SDK. DCAM-API and DCAM-API SDK are compatible with Windows and Linux.

With the increasing sophistication of imaging experiments, comes an increasing need for customized control of lab hardware. Our software engineers have created useful and user-feedback based toolkits for common development environments including MATLAB, LabVIEW and Python.

More details and downloads can be found at www.dcam-api.com

DEVELOPMENT ENVIRONMENTS

MATLAB　LABVIEW　PYTHON

COMPATIBLE WITH

WINDOWS　LINUX

WWW.DCAM-API.COM

Software Support

PC

VARIOUS CAMERAS

- CoaXPress
- CameraLink
- USB
- Gigabit Ethernet
- ⋮

VARIOUS INTERFACE

DCAM-API

HAMAMATSU PHOTONICS
COMMON CAMERA LIBRARY

- Hamamatsu software
- Third-party software
- DCAM-SDK

DEVELOPMENT ENVIRONMENT
FOR CUSTOM SOFTWARE

“Basically, I have been compelled by curiosity.”

—MARY LEAKEY

IGNITING QUESTIONS DETECTING ANSWERS

ORCA®-Quest

CAMERA SPECIFICATIONS

LOW READOUT NOISE
0.27 electrons rms
Ultra-quiet Scan

HIGH QE
90 % @ 475 nm
Back-illuminated qCMOS

HIGH SPEED
120 fps
@ 4096 × 2304 pixels (16 bit)

HIGH RESOLUTION
4096 × 2304
9.4 Megapixels

PIXEL SIZE
4.6 µm × 4.6 µm

DYNAMIC RANGE
25 900 : 1
Ultra-quiet Scan

Imaging Device

ORCA®-Quest

qCMOS® Image Sensor

Product Number

C15550-20UP

Pixel Size

4.6 μm (H) × 4.6 μm (V)

Effective number of pixels

4096 (H) × 2304 (V)

Effective Area

18.841 mm (H) × 10.598 mm (V)

Quantum efficiency	90 % @ 475 nm
Full well capacity (typ.)	7000 electrons
Readout noise (typ.)	
Standard scan	0.43 electrons rms
Ultra quiet scan	0.27 electrons rms
Dynamic range (typ.) *1	25 900 : 1
Linearity error	
EMVA 1288 standard (typ.)	0.5 %

Digital output	16 bit / 12 bit / 8 bit
Exposure time	
Standard scan	7.2 μs to 1800 s
Ultra quiet scan	172.8 μs to 1800 s
Interface	USB 3.1 Gen 1, CoaXPress (Quad CXP-6)
Lens mount	C-mount
Master pulse	
Pulse mode	Free running / Start trigger / Burst
Pulse interval	5 μs to 10 s in 1 μs steps
Burst count	1 to 65 535
Image processing function	Defect pixel correction (ON or OFF, hot pixel correction 3 steps)
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)

Cooling method (Peltier cooling)	**Sensor temperature**	**Dark current (typ.)**
Forced-air cooled (Ambient temperature: +25 °C)	-20 °C	0.016 electrons/pixel/s
Water cooled (Water temperature: +25 °C)	-20 °C	0.016 electrons/pixel/s
Water cooled (max cooling)	Less than -35 °C *2	0.006 electrons/pixel/s

Frame rate (at full resolution)	**CoaXPress**	**USB**
Standard scan	120 frames/s	17.6 frames/s
Ultra quiet scan	5 frames/s	5 frames/s

MODE	**Sensor mode**	**Readout mode**
	Area readout	Full resolution
	Lightsheet readout *3	Digital binning (2×2, 4×4)
	Photon number resolving	Sub-array

TRIGGER INPUT

External trigger input mode	
Area readout, Photon number resolving	Edge / Global reset edge / Level / Grobal reset level / Sync readout / Start
Lightsheet readout	Edge / Start
Software trigger function	
Area readout, Photon number resolving	Edge trigger / Global reset edge trigger / Start trigger
Lightsheet readout	Edge trigger / Start trigger
Trigger input connector	SMA
Trigger delay function	0 s to 10 s in 1 μs steps

TRIGGER OUTPUT

Trigger Output	Global exposure timing output / Any-row exposure timing output / Trigger ready output / 3 programmable timing outputs / High output / Low output
Trigger output connector	SMA

*1 Calculated from the ratio of the full well capacity and the readout noise in Ultra quiet scan

*2 The water temperature is +20° C and the ambient temperature is +20° C

*3 Software such as HCImage is required. For details, please contact your local Hamamatsu representative or distributor.

“If I have seen further,
it is by standing upon the
shoulders of giants.”

—SIR ISAAC NEWTON

IGNITING QUESTIONS DETECTING ANSWERS

The ORCA-Quest quantitative CMOS (qCMOS) camera with Photon Number Resolving functionality is the leap in scientific camera evolution that transforms imaging into imagining. Our journey to create the ORCA-Quest is only the prologue to many epic adventures. These stories are the tales of scientific exploration done with a new and powerful tool.

LET YOUR DISCOVERY BEGIN...

Hamamatsu's Tadashi Maruno and his engineering team are proud to present our next advance in imaging technology: the ORCA-Quest.

Scientists have become the bearers of the torch

The most important discoveries will provide answers to questions that we do not know how to ask and wil…

quest for knowledge

yet imagined.

HAMAMATSU

PHOTON IS OUR BUSINESS

hamamatsucameras.com

Cat No. SCAS0152E01
MAY/2021 HC
Created in the USA