Astronomy

Camera application case-study

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PHOTON IS OUR BUSINESS

INDEX

Image of the front cover

Orion Nebula M42

Lucky imaging in an urban area December 2020
(Equipment: 30 cm telescope, with ORCA®-Quest qCMOS® camera)

SPECIAL INTERVIEW

Adaptive optics

There are several methods for observing exoplanets, and about 4000 exoplanets have been discovered so far using these methods. Of these, only around 10 to 20 exoplanets have been confirmed by "direct imaging" with an observation device using a telescope. The main mission of our research is to improve the accuracy of direct imaging observation equipment and capture the light emitted by as many planets as possible.

Adaptive optics is a technique that immediately corrects a wavefront disturbed by atmospheric fluctuations and obtains the clearest star image without distortion within the performance limits of a telescope. It is also a key component of the observation device.

In order to achieve real-time and highly accurate wavefront correction, high-speed readout performance and high resolution are required. In addition, some times wavefront correction is performed in situations where the number of photons is very small, such as darker celestial bodies and laser artificial stars, which requires high sensitivity in the camera.

What is needed to improve performance, and what will be achieved once the ultimate performance is reached? We asked Dr. Kodai Yamamoto of the Astronomical Observatory, Graduate School of Science, Kyoto University, who is working on direct imaging of exoplanets using a giant telescope, about the current performance of adaptive optics and future prospects of using them.

Interview

Kodai Yamamoto, Ph.D. Astronomical Observatory,
Graduate School of Science, Kyoto University

The desire to directly image the actual light emitted by planets using telescopic observation equipment

Q Can you tell us about the current status of planetary observation using adaptive optics?

We are currently building an observation device to be installed on the newly built "Seimei", the largest telescope in Japan, in Okayama Prefecture. This device will be used for direct imaging of exoplanets.

The worlds first direct optical detection of an exoplanet occurred in around 2008. Since that time only 10-20 others have been confirmed this way, out of around 4000 exoplanet discoveries. So the fact that we have directly imaged only 10 to 20 planets means that the detected number of planets is very small.

The reason for the small number is that the performance of observation devices for direct imaging is still lacking. However, an additional challenge is that exoplanets are very dark objects located near fixed stars that emit their own light, so it is very difficult to detect their light.

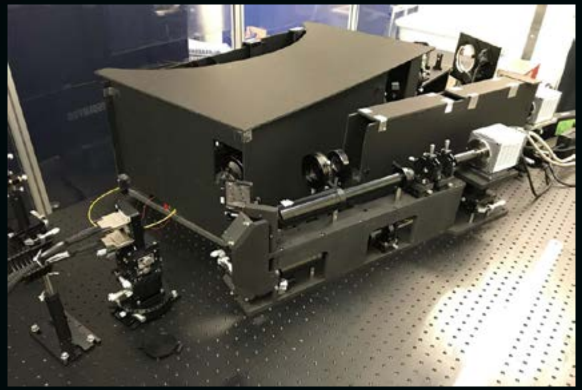
We have developed an exoplanet imager "Second-generation Exoplanet Imager with Coronagraphic AO (SEICA)" for the previously mentioned telescope "Seimei" and are trying to find darker celestial bodies. However, we have not yet achieved the performance needed to detect undiscovered planets.

Some of the world's largest telescopes, such as the Subaru Telescope and the VLT in Chile, have apertures of 8 m to 10 m, and high detection performance. Since the detection performance of a telescope increases with its size, the performance of "Seimei", whose aperture is less than half of those larger ones, is inferior. Although the performance of observation equipment is getting better and better, it is still not good enough to detect very dark objects near fixed stars.

Lay the foundation for direct imaging of planets with a large telescope

Q The adaptive optics device "SEICA" was developed to find exoplanets by direct imaging. I'm sure that further performance improvements will be required in the future. But what kind of results do you expect to achieve by improving its performance?

There are two goals for "SEICA". One is to detect exoplanets, and the other is to serve as a test-bed for technologies that can be applied to large telescopes in the future.



Adaptive optics device "SEICA"

As mentioned earlier, when trying to develop a new technology it is actually very difficult because the target is dark and very close to a fixed star. This is not the only reason why it is difficult to observe. Another major influence on the quality of an image is the atmosphere. When the atmosphere is disturbed, the image is distorted in the form of the so-called blinking of stars, and the outline of the image is blurred or shifted, making it difficult to obtain a clear image. Adaptive optics have been developed to counteract the effects of such atmospheric turbulence.

While our main goal is to elucidate the actual state of planets by direct imaging of planets, we also hope that our research will result in improving the performance of the adaptive optics system and laying the foundation for direct imaging of planets in the future with a large optical telescope equipped with adaptive optics.

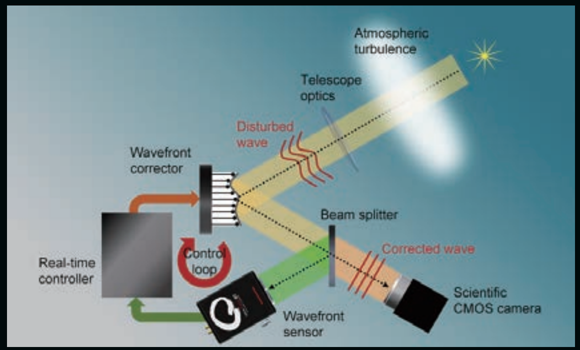
Improving the performance of wavefront sensors is the key to evolution

Q I have heard that improving the performance of adaptive optics is essential for achieving the first goal, "Detection of exoplanets". What is the most necessary thing for that?

Among adaptive optics devices is an extreme adaptive optics device called "Extreme AO". The Extreme AO is also used in the Subaru Telescope, but the one we have developed uses an FPGA to control the wavefront more quickly and precisely. The reason why we are pursuing such high-precision wavefront control is that, again, how to cancel out atmospheric turbulence is directly related to the accuracy of imaging.

In fact, the shape of the atmosphere itself does not change so much. If you look at it at a frequency of about 1 kHz or 6.5 kHz, it keeps almost the same shape, but when the wind blows, it gets swept away. So the wavefront shape you are watching thinking "this is it" will drift away the next moment and you will be looking at another shape. Therefore, the time-delay between measurement and correction appears as a shape of error. Strictly speaking, it not only corrects while measuring the wavefront in real time, but also controls by combining a control-algorithm that predicts and corrects the wavefront ahead of the wind.

The conventional "tile-measurement" wavefront sensors check the shape of a wavefront by looking at the inclination of each point on the wavefront and integrating it back to the original shape, but because of the integral process, measurement errors at each point propagate to the overall shape measurement. However, with the "phase measurement" used in our adaptive optics equipment, you can directly measure "how high is this position on the wavefront."



As the phase can be measured directly, errors are less likely to occur. Since adaptive optics for direct imaging of exoplanets requires high-speed and high-precision wavefront control, so does wavefront measurement. Improving the performance of wavefront sensors is essential for the evolution of adaptive optics.

Search for life outside of Earth

Q I would like to ask you in detail more about the second question, “application to large telescopes”. Furthermore, can you tell us about your ideas as you pursue your research?

At the level of studying exoplanets, I'm sure that what researchers think is the ultimate is “searching for life in places other than the earth.” Of course, it is absolutely impossible to optically find life on the surface of a planet, so I think there is a desire to properly investigate things such as the appearance of plants, the presence of oxygen, and the composition of the atmosphere, which would bring us a little closer to discovering life.

In other words, direct imaging means that you can do spectroscopy. If you can do spectroscopy, you can get crucial clues as to what kinds of molecules are present. I believe that the ultimate goal of our generation is to use direct imaging to get clues as to whether life exists or not, and if so, what kind of life it is.

Aiming for a device that eliminates the effects of turbulence

When we say “ultimate” in terms of device development, the ultimate goal is to create an adaptive optics device that completely eliminates the effects of atmospheric turbulence. Compared to the adaptive optics devices that existed about 20 years ago, the ones that are currently being developed have much better performance, and they are getting closer to the level of making a beautiful wavefront, but are still not the ultimate adaptive optics in the true sense. It requires faster measurement, computing, and correction. Without these pursuits, the ultimate goal cannot be achieved.

Cameras are also an important factor in improving device performance

Q The fact that a high-speed and high-precision wavefront sensor is essential for faster calculation, computing, and correction means that the 2D sensor that captures images; that is, the camera side, is also required to have the same high level of performance, right?

That's right. After all, what we want most is high speed and low noise. As I said earlier, there is a delay in the time from measuring a wavefront to applying correction, and that delay causes a temporal error. So corrected wavefront images taken by the camera are almost speed limiting to it. The faster the acquisition time, the shorter the exposure time, and the number of photons that can be detected will decrease per frame. That's why I said high speed and low noise, but there is a real trade-off between the two, so the faster you go, the higher the readout noise and photon noise will be, and in contrast, if you try to lower them, you will naturally see temporal errors in the image.

In order to resolve the trade-off between the two, predictive control has been introduced into the control algorithm. However, it is difficult to implement complex control because of the cost of the computation, both in terms of hardware and software. If you build a dedicated circuit from measurement to control, you can shorten the calculation time to the limit, but the dedicated circuit is expensive and not easy to modify. A general PC also has the advantage of being able to freely develop and change algorithm. Therefore, we have adopted an FPGA, which is an intermediate device between a PC and a dedicated circuit, as a control device.

Even if the algorithm eliminates the trade-off, it is still very important to select a camera to be used for the wavefront sensor. We try to carefully select and adopt the one that has both high speed and low noise.

— Thank you very much.

Interviewee

Kodai Yamamoto, Ph.D.
Astronomical Observatory, Graduate School of Science, Kyoto University

Researcher at the Astronomical Observatory of the Graduate School of Science, Kyoto University (inter-university collaboration). D. (science). Completed doctoral program at the Graduate School of Science, Osaka University in 2014.

Yamamoto specializes in infrared astronomy, and engages in direct imaging observations of extrasolar planets, and development of observation equipment.

The cameras he uses

ORCA® -Flash4.0 V3 Digital CMOS camera

SPECIAL INTERVIEW

Upper atmosphere imaging

The upper atmosphere refers to the atmosphere around 80 km to 400 km in height. It is in the boundary region between the Earth's atmosphere and outer space, and part of the atmosphere is in an ionized plasma state. The interaction between the plasma and the atmosphere causes auroras in polar atmosphere in both hemispheres. In the mid and low latitudes, there is also a luminous phenomenon called nighttime airglow.

In a word, "observation of aurora" means that there are various types of aurora and various points to observe. It is a very diverse field as a research theme, and not only is an aurora mysterious in appearance, but the phenomena are not yet fully understood? As a result, it is said to be a mysterious phenomenon.

This time, we asked Professor Yoshizumi Miyoshi of the Institute for Space-Earth Environmental Research, Nagoya University, who is working on high-speed imaging of the luminescence phenomenon occurring in the brilliance of the aurora, about his measurements of the dynamics of the upper atmosphere and the importance of high sensitivity, high resolution, and high speed imaging.

Interview

Yoshizumi Miyoshi, Ph.D.
Institute for Space-Earth Environmental Research (ISEE), Nagoya University

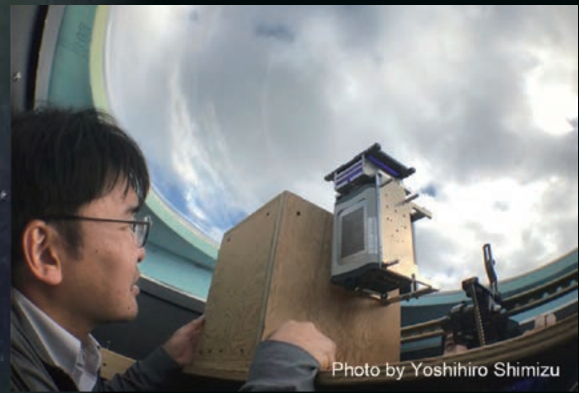
Aurora is a clue to what is happening in outer space

Q Can you tell us what you can learn by observing the aurora, and the purpose of the observation?

Aurora is a phenomenon in which electrons and ions in outer space fall into the upper atmosphere of the Earth and emit light. Therefore studying the brightness, movement and shape of the aurora can give us clues to what is happening in outer space. There is a long history of aurora observations, within this history new devices to aid observation have been introduced, such as cameras, CCDs, EM-CCDs and CMOS.

The era of high-speed precision aurora observation has come, and we are discovering more and more drastic changes in the aurora and fine structures that cannot be seen with the naked eye. In other words, the fact that there is a mechanism that creates such fast changes and small changes in outer space leads to an understanding that such a new mechanism is occurring in outer space. Of course, auroras are beautiful and enjoyable to look at, but it is already essential for space research to chase fast, small, and faint luminescence that occur within these phenomena, which are invisible to the eye. I feel the arrival of a new era through cutting-edge aurora research.

To briefly introduce the efforts of our research group, for example, there is a satellite called Arase, which was launched by JAXA in 2016, and it observes the variations of electrons and ions, called plasma, as well as fluctuations of electric and magnetic fields, called plasma waves, in space. Currently, an EM-CCD camera is observing the aurora glowing in the upper atmosphere, which is connected to the Arase satellite by magnetic field lines. By combining satellite and ground-based observations, we are investigating the relationship between auroras observed by the EM-CCD camera and phenomena occurring in space; for example, "What is happening in space when this kind of aurora is observed?" We have been continuously imaging auroras at a speed of 100 Hz using the EM-CCD camera, and we are seeing a world that we could only see at this high speed, so we hope to clarify the mechanism that produces such phenomena.



Observation (camera: ImagEM® X2 EM-CCD camera)

Faster, finer, and wider field of view. A camera that evolves with the progress of research is needed

Q You have told us about the history of the improvement of camera detection performance as research progressed. Is there anything you want to see in the evolution of cameras for current and future research?

Of course, what to look at in the aurora depends on researchers, but I think there are two major factors. The first is the direction of "faster, finer, higher resolution and higher time resolution". On the other hand, if you pursue such a direction, you will end up with a narrow field of view, even though it has high temporal resolution and spatial resolution. The world is entering the era of 4K displays and 8K, and I would like to aim for the same thing with aurora observation, and would like to have a camera that makes such things possible.

The other is that aurora is a phenomenon that occurs in various places on the earth, so we would like to deploy cameras at multiple points so that the fields of view of each camera overlap, and connect them all with a network to capture images with high temporal and spatial resolution. For example, the aurora that can be seen from a single location is about 500 km square. However, even if you go to the next longitude, or south or north, you may see the aurora continuously. In order to observe such aurora, recently, a method called a network has become highly advanced, in which many cameras are placed here and there to observe auroras on global scale. We are thinking not only to take images with high spatial resolution and high temporal resolution, but also to observe the fluctuation of the aurora on a pan-global scale by laying out cameras in a row. To do that, we need to have good-performance cameras in many places, and I hope that will be possible.

"Space weather forecast" to work on as basic research

Q You have been giving lectures for high school students with the word "space weather". Do you see such things in real time in your daily work?

Since I work at a university, I am doing basic research on space weather and space weather forecasts. Ordinary weather forecasts are sent by the Japan Meteorological Agency, but in the case of space weather, they are sent by the National Institute of Information and Communications Technology in Japan. We are conducting basic research that leads to higher prediction accuracy, and research on changes in the space environment. In that research, we analyze data from artificial satellites and ground observations, perform simulations, and install EM-CCD and CMOS cameras in Scandinavia and North America for observation.
It is often said that auroras are "a manifestation of space weather". For example, when there is an explosion on the sun, a large amount of plasma, much larger than the Earth, flies from the sun to the Earth.

When this happens, the space around the Earth is disturbed and becomes a "storm", which may affect satellites and communications.

Our camera installed at the aurora observatory at the Poker Flat Research Range of the University of Alaska

When it gets really bad, it can affect aircrafts flying above us, so we sometimes have to take measures such as lowering the latitude of our flights because aircraft flying over the North Pole are likely to be affected.
At this time, the aurora may be stronger than usual, and may also be seen at lower latitudes where it is not usually seen.

The phenomena happening on Earth and in space are all connected, so studying changes in the aurora is directly related to understanding how the connection between the Sun and Earth is changing and what is happening in space. It's not just studying the aurora.

—Thank you very much.

Interviewee

Yoshizumi Miyoshi, Ph.D.
Institute for Space-Earth Environmental Research, Nagoya University

Professor, Institute for space and earth environment, Nagoya University. D. (science). After graduating from the graduate school of science, Tohoku University, he was a research fellow of the Japan Society for the Promotion of Science (JSPS) and a visiting scholar at the University of New Hampshire, USA. From 2004, he was a research associate and assistant professor at the Institute for Solar-Terrestrial Environmental Studies (now the Institute for Space and Earth Studies), Nagoya University, and then an associate professor before assuming his current position in 2018. Project scientist of the JAXA ERG (Arase) satellite project.

Miyoshi specializes in space physics and terrestrial and planetary magnetospheric physics. He has been engaged in the analysis and simulation of satellite observation data and ultrafast imaging observations of aurorae. He received the Young Scientist Award from the Minister of Education, Culture, Sports, Science and Technology, the Japan Geoscience Union's Earth and Planetary Science Promotion Nishida Award, Society of Geomagnetism and Earth, Planetary and Space Sciences Tanakadate Award, the Inoue Science Award, and others.

The cameras he uses

ORCA®-Flash4.0 V3 Digital CMOS camera

ImagEM® X2 EM-CCD camera

TOPIC

Solar imaging

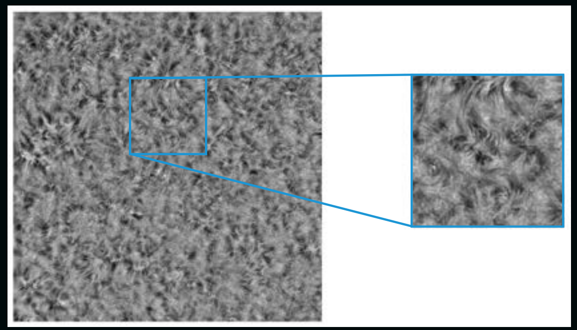
Flares caused by the explosive activity of the sun are a serious problem for astronauts working in outer space, because they emit large amounts of radiation such as X-rays and gamma rays. On the Earths surface we are protected from this radiation by the atmosphere. However, large-scale solar flares can cause magnetic storms which can negatively impact our daily lives, such as causing power outages.

There is still much that is unknown about the activity of the sun, and research to predict the onset of flares based on the movement of sunspots and magnetic fields is becoming very important. In order to trace the internal structure of solar flares and their time evolution in detail, detectors with high resolution, high speed, and high dynamic range are required.

Information provided

Yunnan Astronomical Observatory ONSET

The Optical Infrared Solar Flare Monitoring Telescope (commonly known as "ONSET") was constructed in Yunnan Province, China in 2011 and has been put into operation. ONSET can simultaneously acquire partial images of the sun, solar corona, chromosphere, and photosphere images in the full-disk or partial-disk (with a field of 10') at He (He I 10830), Hα, and two white light wavelengths (360 nm and 425 nm). Thus, ONSET can acquire complete three-dimensional images of solar flares at different altitudes in the solar atmosphere, contributing to all kinds of research on solar flares. It is also capable of high temporal resolution and high spatial resolution observations to reveal the spatial and temporal fine structure of solar flares.



Solar flares imaged by ONSET
(Using ORCA®-Flash4.0 V3 Digital CMOS camera)

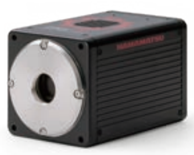
ONSET uses a vacuum lens telescope to greatly reduce scattered light from the instrument and prevent interference from air convection. Observations are performed by automatic computer control. The telescope consists of four telescopes, with the following specifications (1) He (10830) filter / aperture 275 mm / solar image diameter 24 mm / operating wavelength: 1083.0 nm ± 0.4 nm, (2) H α filter / aperture 275 mm / solar image diameter 24 mm / operating wavelength: 656.3 nm ± 0.4 nm, (3) White light filter / 200 mm aperture / 24 mm solar image diameter / Operating wavelength: 360.0 nm ± 1.5 nm and 425.0 nm ± 1.5 nm, (4) Photoelectric guide / 140 mm aperture included.

ONSET in the vast land of Yunnan

ONSET has acquired a large number of high quality solar images with a data volume of over 10 TB, including rare data such as solar white light flares. Considering the uniqueness of the time zone, these data are internationally unique. These research results are published in prestigious academic journals; The Astrophysical Journal, ApJ and The Astronomy and Astrophysics, A&A.

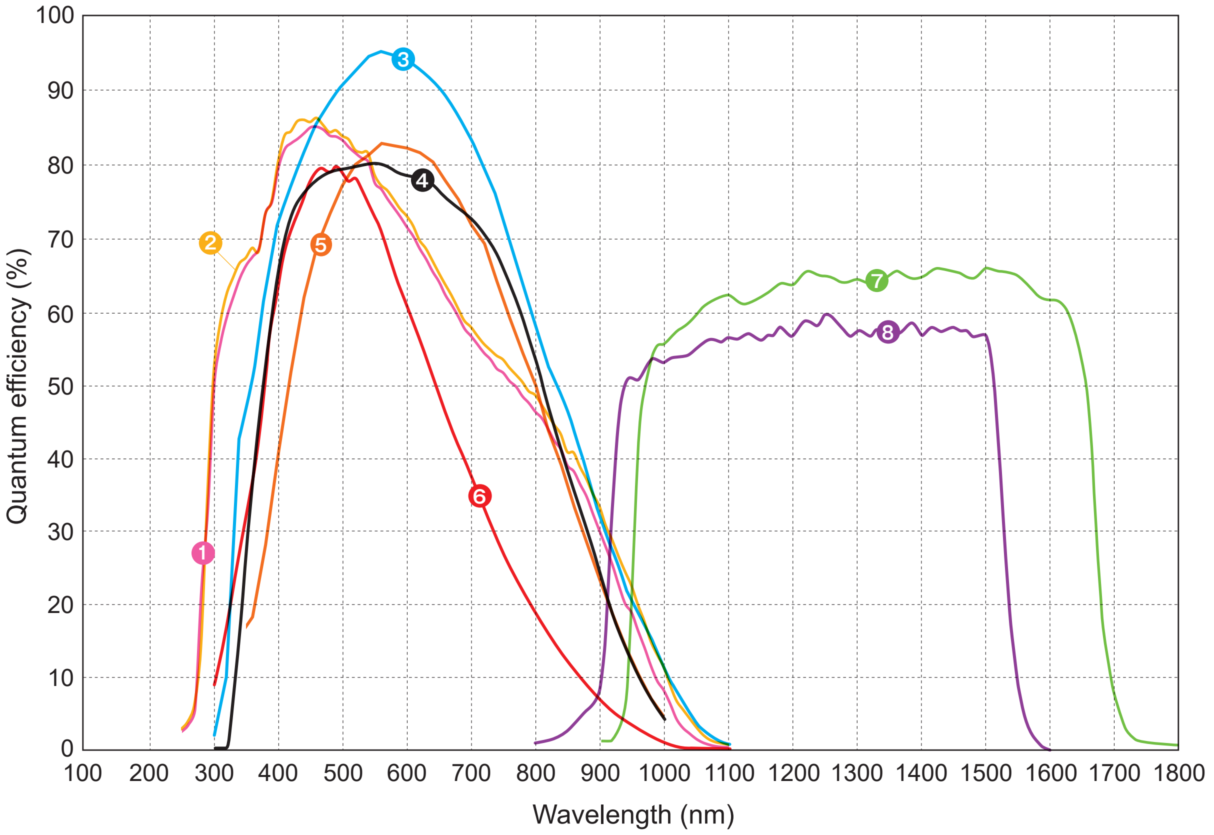
Camera line up

For detailed information https://www.hamamatsu.com/all/en/product/cameras.html

	Visible to near-infrared							Near-infrared			
Product name	ORCA®-Quest 2 qCMOS® camera	ORCA®-Fire Digital CMOS camera	ORCA®-Fusion BT Digital CMOS camera	ORCA®-Fusion Digital CMOS camera	ORCA®-Flash4.0 V3 Digital CMOS camera	ORCA®-Flash4.0 LT3 Digital CMOS camera	ORCA®-spark Digital CMOS camera	InGaAs camera			
Product number	C15550-22UP	C16240-20UP	C15440-20UP	C14440-20UP	C13440-20CU	C11440-42U40	C11440-36U	C16741-40U	C14041-10U	C12741-03	C12741-11
Appearance											
Image sensor type	Area sensor							Area sensor			
Sensitivity wavelength range (nm) (Spectral response: See P14)	250 to 1000		350 to 1000					400 to 1700	950 to 1700		900 to 1550
	1	2	3	4	5	5	6	*3	7		8
Effective number of pixels (H×V)	4096 × 2304	4432 × 2368	2304 × 2304		2048 × 2048	2048 × 2048	1920 × 1200	1280 × 1024	320 × 256	640 × 512	
Pixel size (μm) (H×V)	4.6 × 4.6		6.5 × 6.5				5.86 × 5.86	5 × 5	20 × 20		
Effective area (mm) (H×V)	18.841 × 10.598	20.387 × 10.892	14.976 × 14.976		13.312 × 13.312	13.312 × 13.312	11.25 × 7.03	6.40 × 5.12		12.8 × 10.24	
Full well capacity (electrons) (typ.) *1	7000	20 000	15 000		30 000	30 000	33 000	–			300 000
Dynamic range (typ.) *1	23 000:1	20 000:1	21 400:1		37 000:1	33 000:1	5000:1	–			
Cooling method	Forced-air cooled Water cooled	Forced-air cooled	Forced-air cooled Water cooled			Forces-air cooled	–	Forced-air cooled Natural-air cooled	Forced-air cooled		Forced-air cooled Water cooled
Cooling temperature (°C) *1	-35 (Water cooled)	+20	-15 (Water cooled)		-30 (Water cooled)	+10	–	+15 (Forced-air cooled)	+10		-70 (Water cooled)
Readout speed (frame/s) (Full resolution) *1	120	115	89.1		100	40	64.9	71.53	216.6	59.774	7.2
Readout noise (electrons) (rms typ.) *1	0.30	1.0	0.7		1.4	1.5	6.6	–			500
Dark current (electrons/pixel/s) (typ.) *1	0.006 (Water cooled)	0.6	0.7 (Water cooled)	0.2 (Water cooled)	0.006 (Water cooled)	0.6	–	–			130 (Water cooled)
Interface	CoaXPress (Quad CXP-6) USB 3.1 Gen 1		CoaXPress (Dual CXP-6) USB 3.0 *2		Camera Link USB 3.0 *2	USB 3.1 Gen 1	USB 3.0 *2	USB 3.1 Gen 1	USB 3.0 *2	USB 3.0 *2 EIA	Camera Link
Applications	Life science imaging Quantum technology Astronomy Semiconductor inspection Synchrotron imaging Electron microscope	Life science imaging Synchrotron imaging Electron microscope		Life science imaging Semiconductor inspection Synchrotron imaging Electron microscope		Life science imaging Semiconductor inspection	Life science imaging Synchrotron imaging	Semiconductor inspection Food inspection Analysis/spectroscopy			Life science imaging Semiconductor inspection

*1 Depends on the mode and conditions. For details, refer to each product catalog.
*2 Equivalation to USB 3.1 Gen 1.
*3 For detailed information, please refer to product catalog.

Spectral response



1 CMOS ORCA®-Quest 2

2 CMOS ORCA®-Fire

3 CMOS ORCA®-Fusion BT

4 CMOS ORCA®-Fusion

5 CMOS ORCA®-Flash4.0 V3
CMOS ORCA®-Flash4.0 LT3

6 CMOS ORCA®-spark

7 InGaAs InGaAs camera C14041-10U
InGaAs InGaAs camera C12741-03

8 InGaAs InGaAs camera C12741-11

Note

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