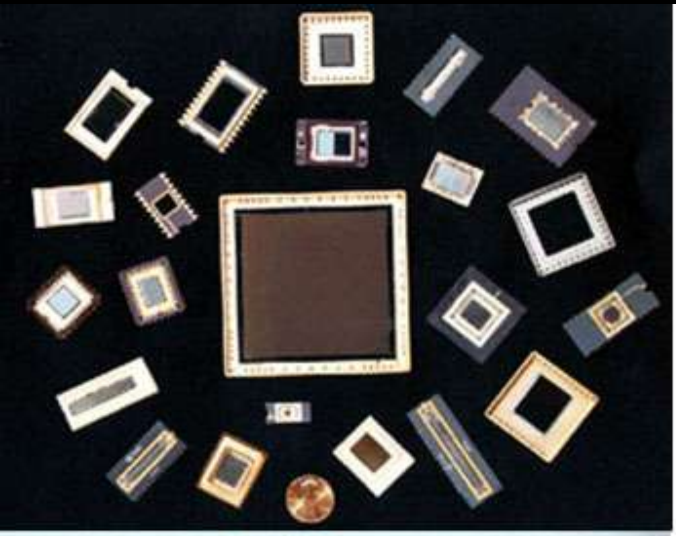
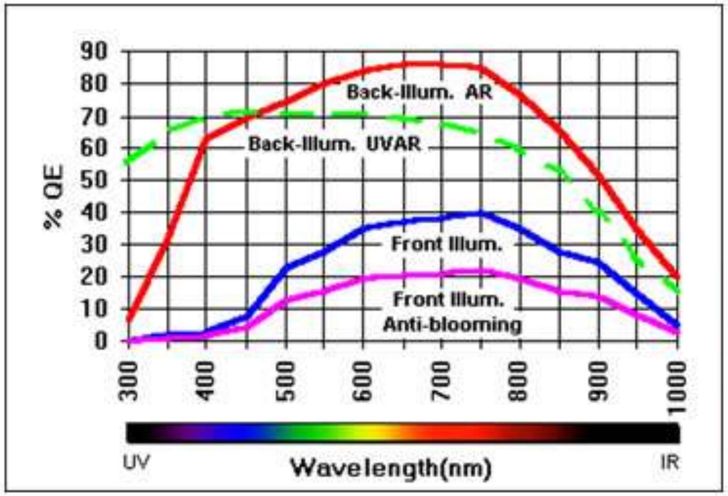
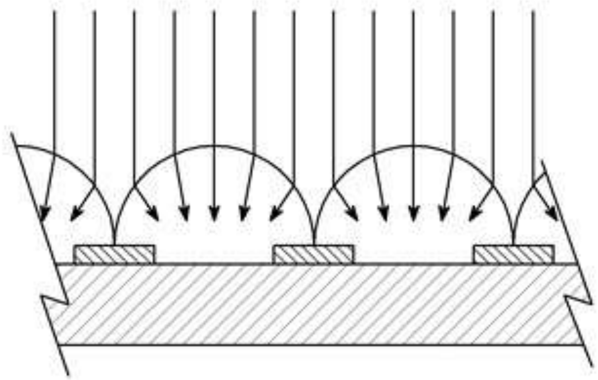
Basic CCD imaging

CCD Cameras





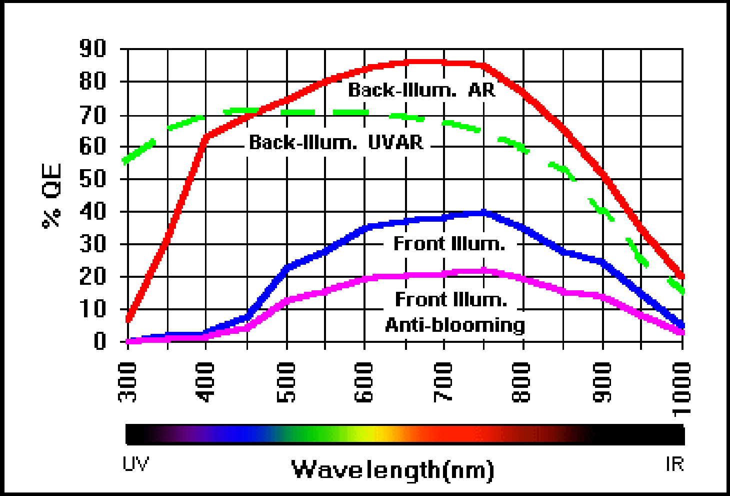


There are basically four different kinds of digital cameras.

- Dedicated, Cooled Astronomical CCD Cameras (CCD)
- Digital SLR Cameras (DSLR)
- Digital Snapshot Cameras (DSC)
- Webcams

HISTORY (CCDs):

- Conceived in **1970** at Bell Labs
- Electronic Analogue to Bubble Memory > a bit = packet of charges (e-) or holes (h+)
- Charge detection amplifier gives an external voltage
- Charge packets read one at a time > Serial Device
- **1973**: JPL initiates Scientific Grade large array CCD program
- **1974**: Fairchild 100x100 on an 8-inch telescope produces first astronomical CCD image



Why Astronomers Love CCDs:

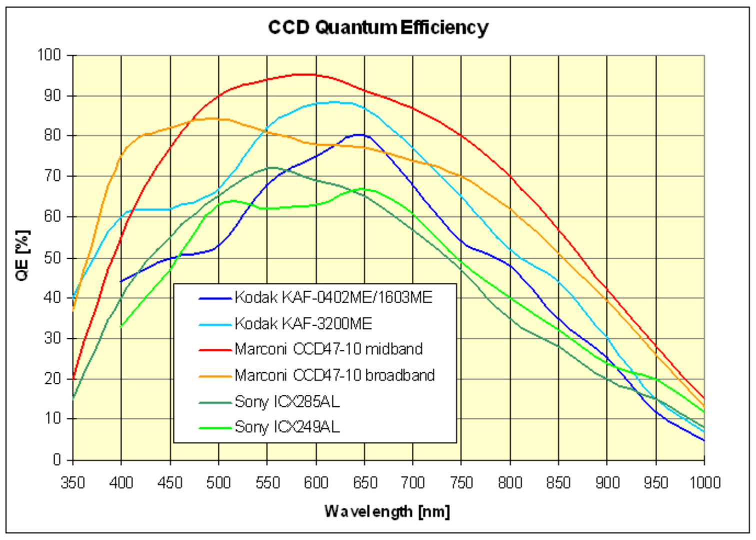
- High QE compared to photographic media
- High Linearity
- Large Dynamic Range

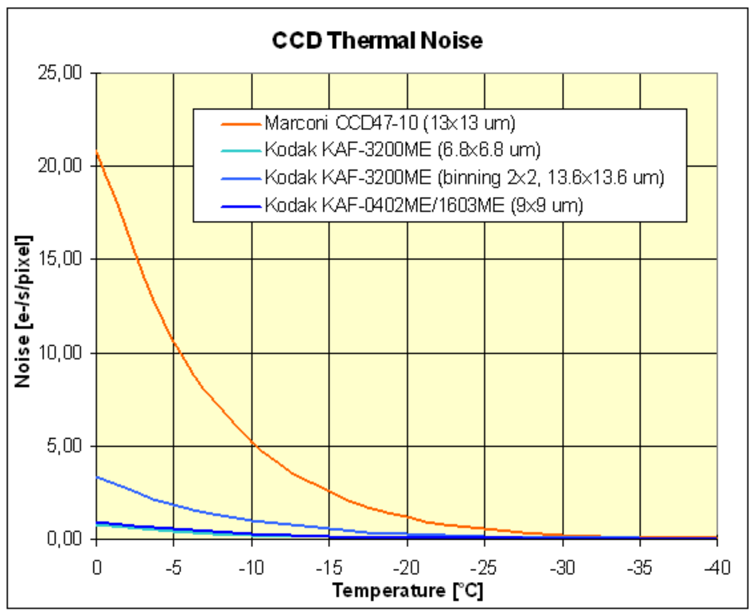
Characteristics of an Ideal Detector:

- 100% QE
- Perfectly Uniform Response
- Noiseless
- Unlimited Dynamic Range
- Completely Understandable Characteristics

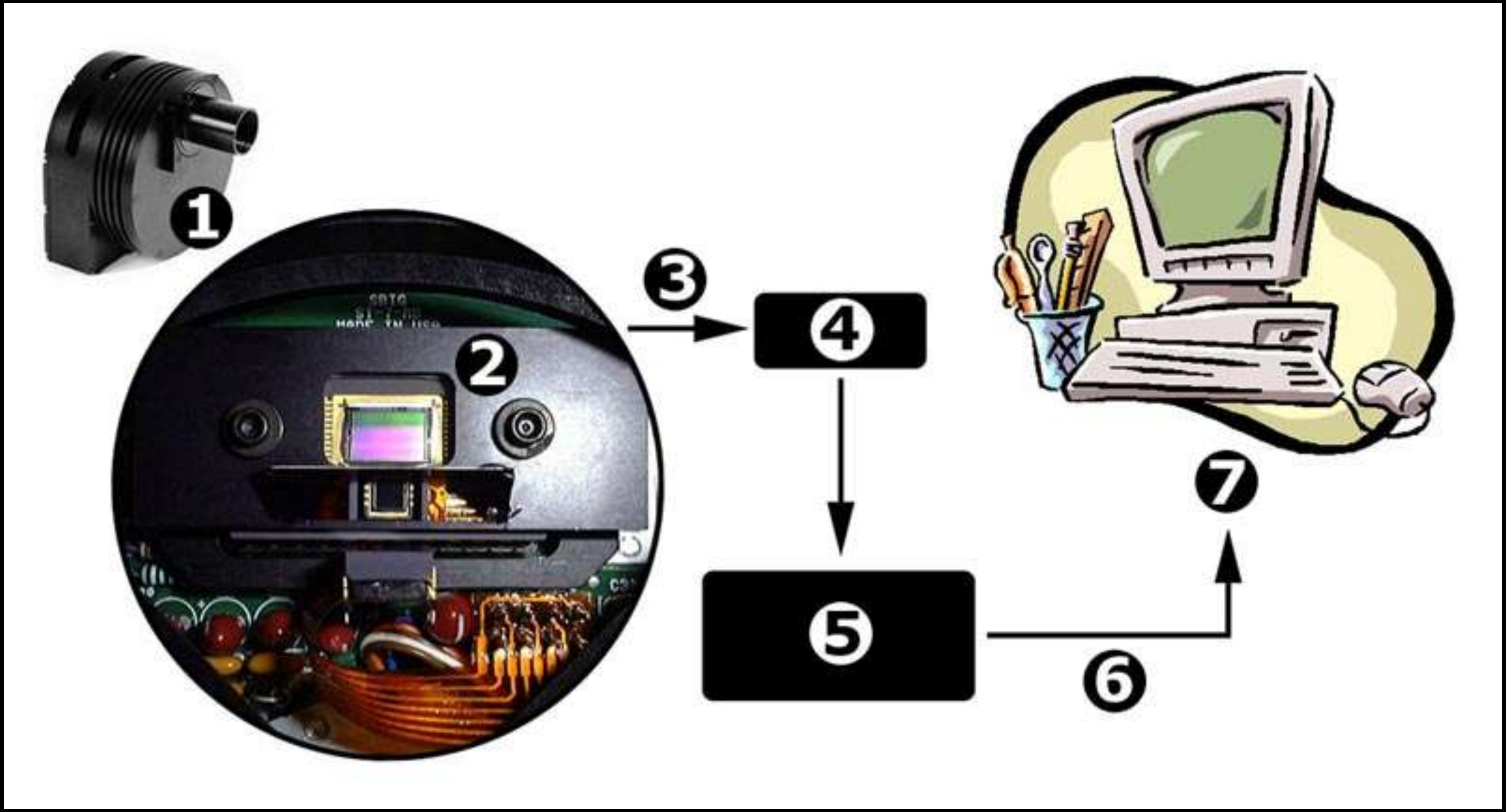
Early Limitations:

- Low area coverage
- poor blue response
- Read Out Noise Dominated for Spectroscopy
- Low light level deferred Charge Transfer Problems



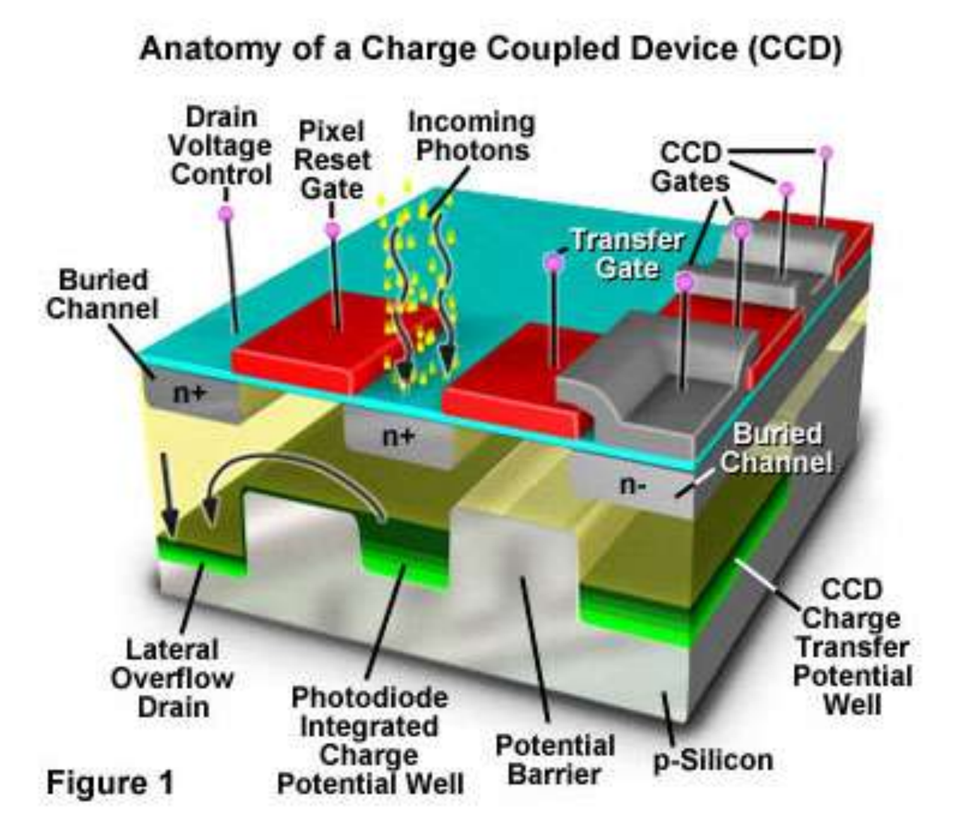


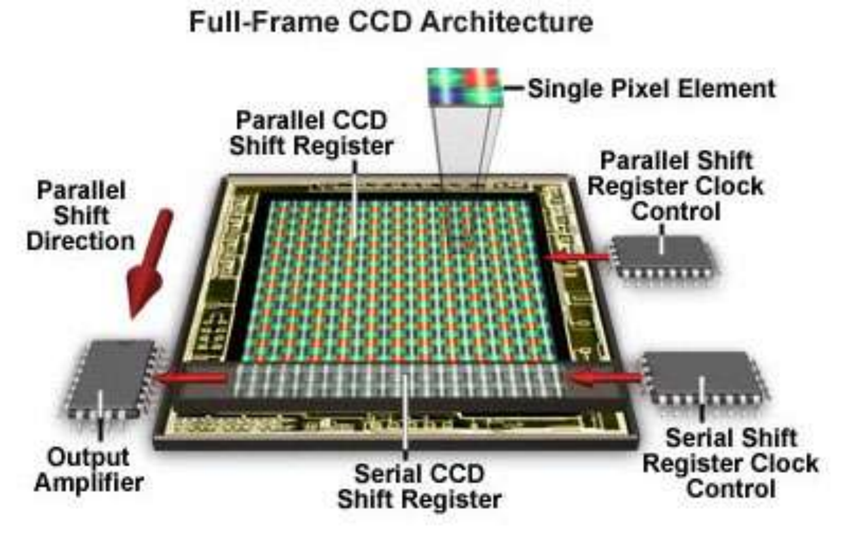
CCD Cameras have been available to amateur astronomers since the late 80's with the introduction of the **SBIG ST-4**. CCD is the acronym of "**C**harge **C**oupled **D**evice". The way a CCD array transforms an image into a computer file is quite simple in principle. Light falling on a grid of detectors produces a pattern of electric charges, which are measured, converted to numbers, and stored in a computer.

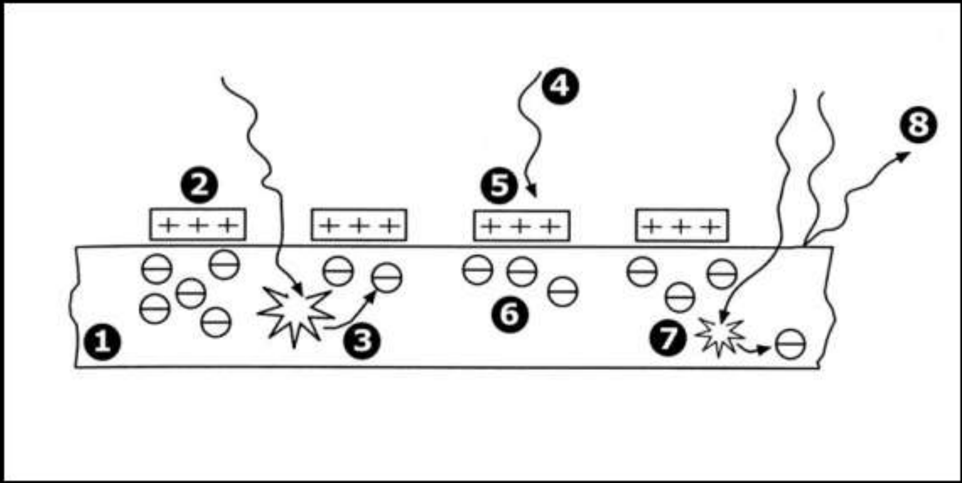


1- CCD camera, 2- CCD detector, 3- Reading, 4- Amplifier, 5- A/D converter, 6- Digitization , 7- Download

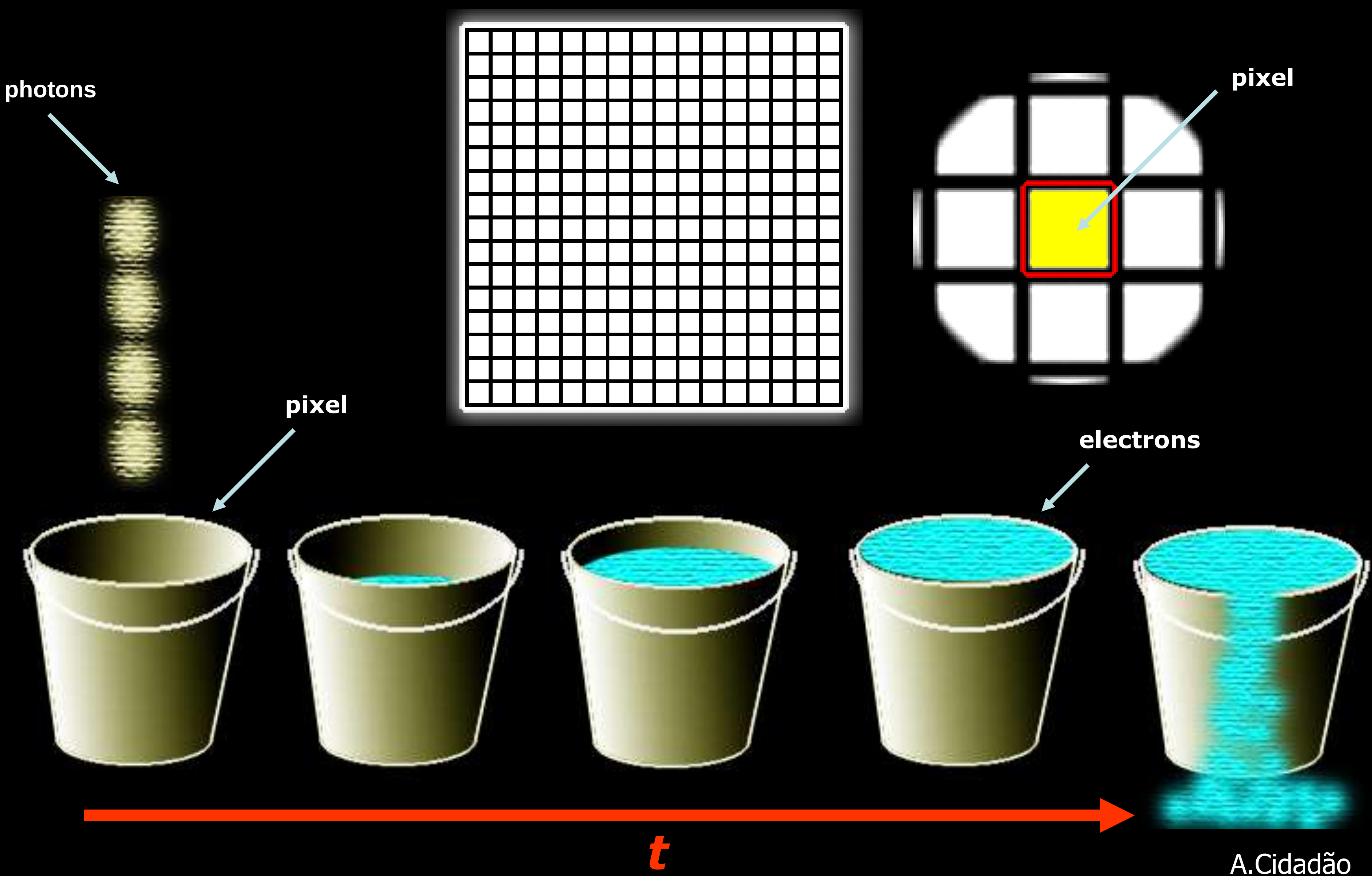
Charge-coupled devices (**CCDs**) are silicon-based integrated circuits consisting of a dense matrix of photodiodes that operate by converting light energy in the form of photons into an electronic charge. Electrons generated by the interaction of photons with silicon atoms are stored in a potential well and can subsequently be transferred across the chip through registers and output to an amplifier.





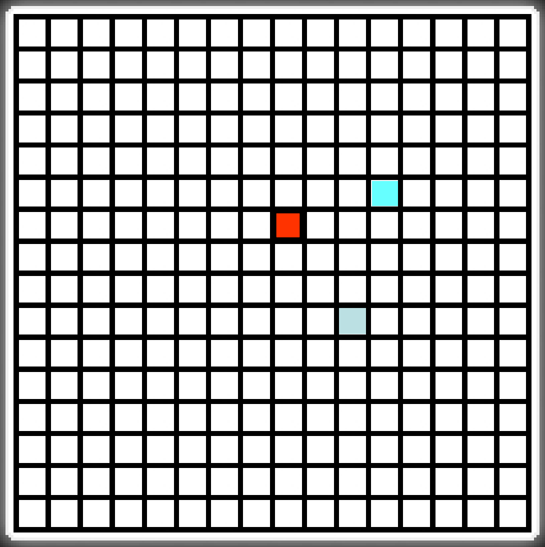


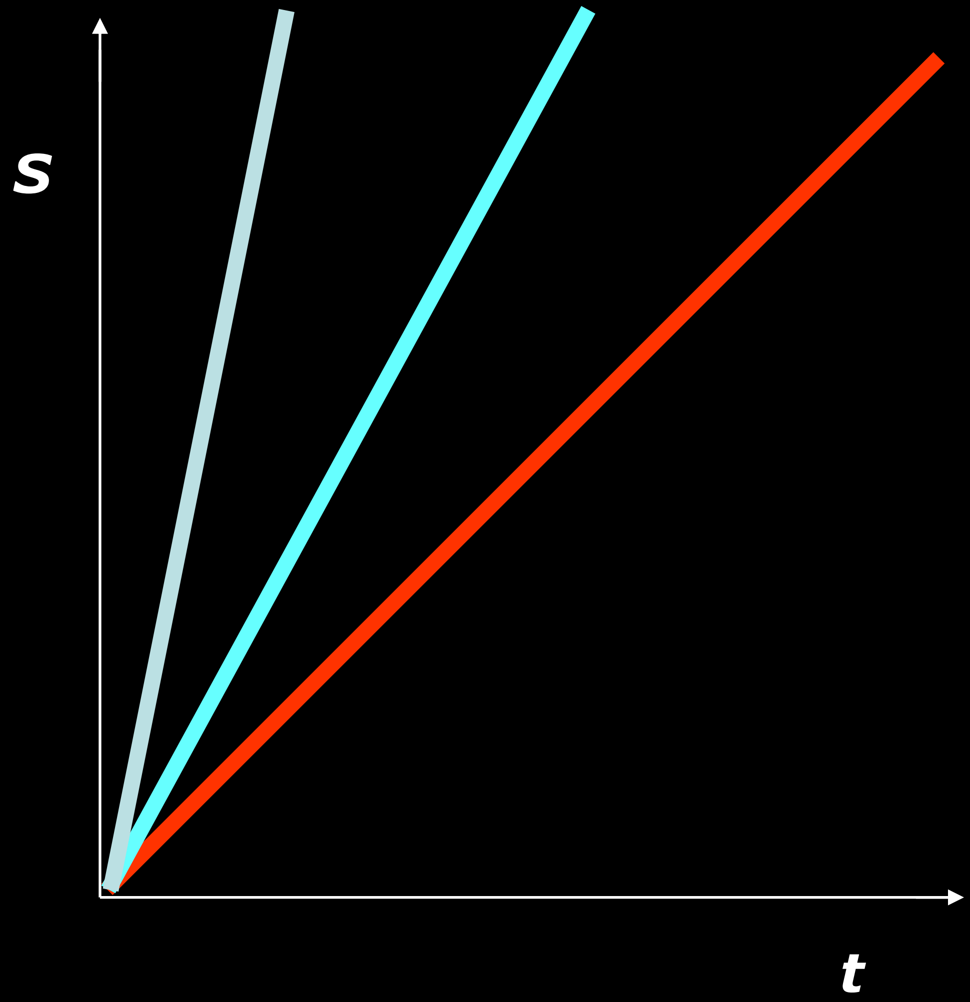
What is a *"CCD"* ?



A.Cidadão

CCD Cameras - *("dark")*

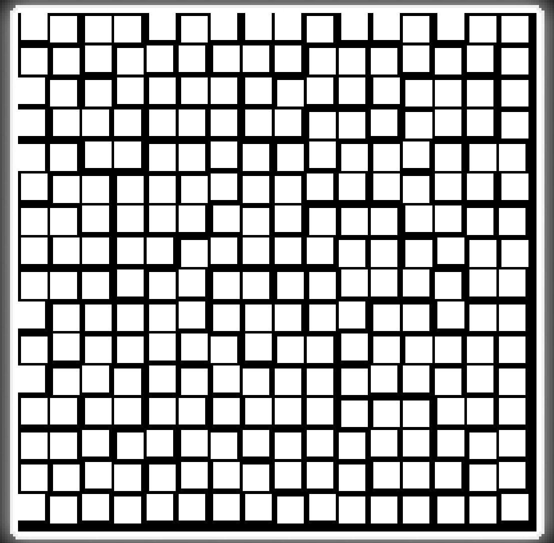


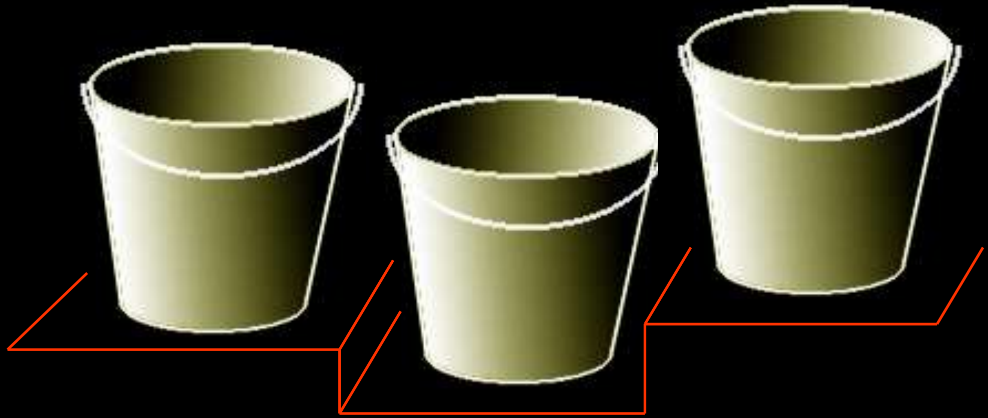


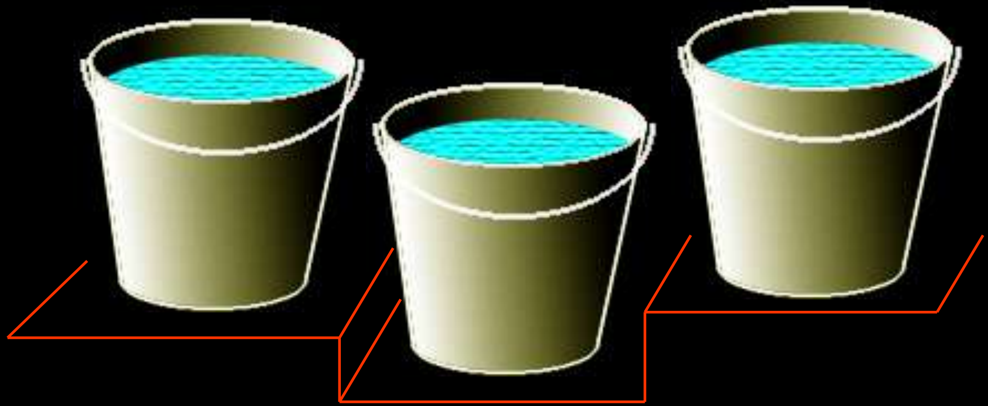
DARK FRAME = BIAS FRAME + THERMAL FRAME

A.Cidadão

CCD Cameras - *("bias")*



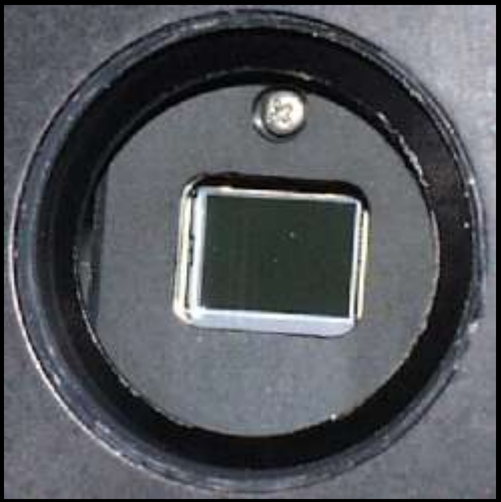


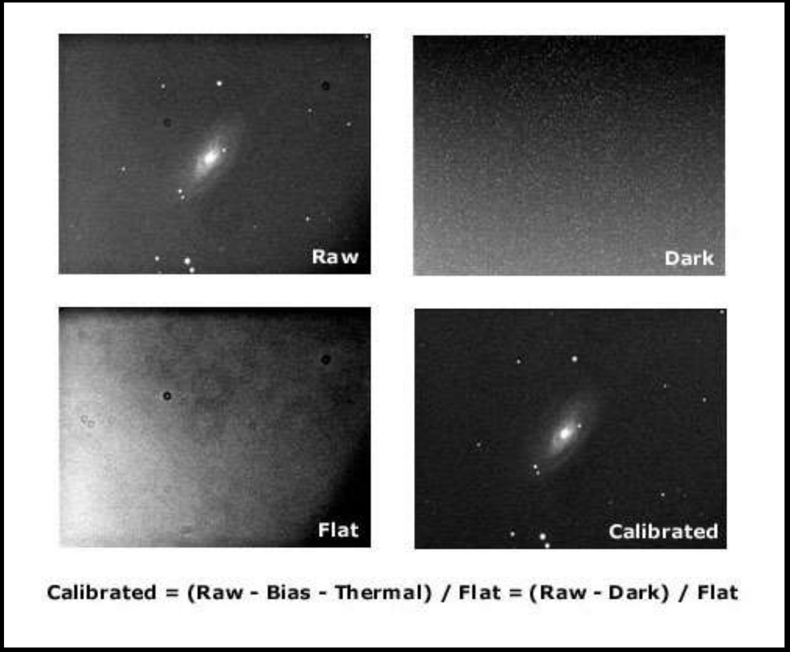


DARK FRAME = BIAS FRAME + THERMAL FRAME

A.Cidadão

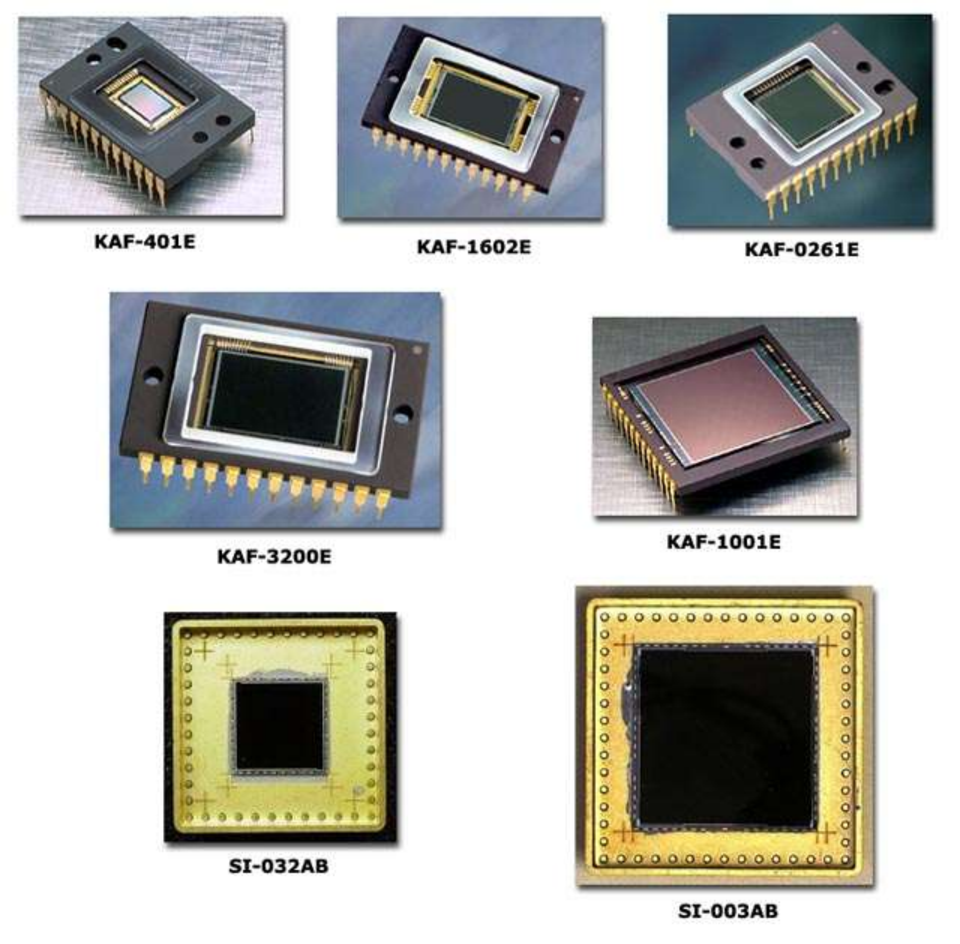
CCD Cameras - *("flat")*



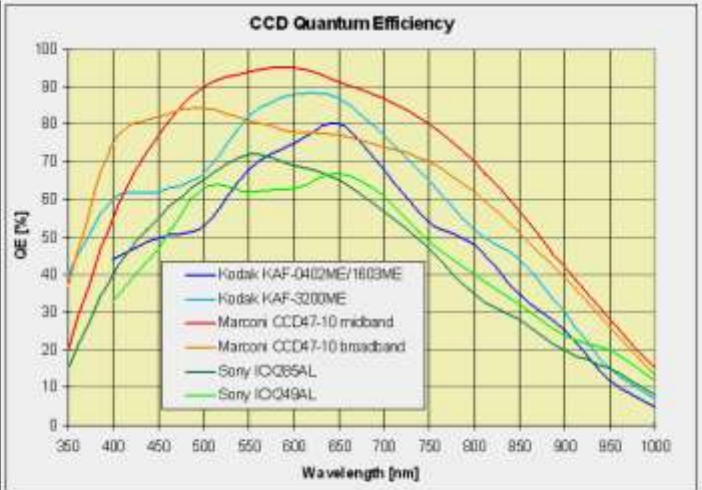


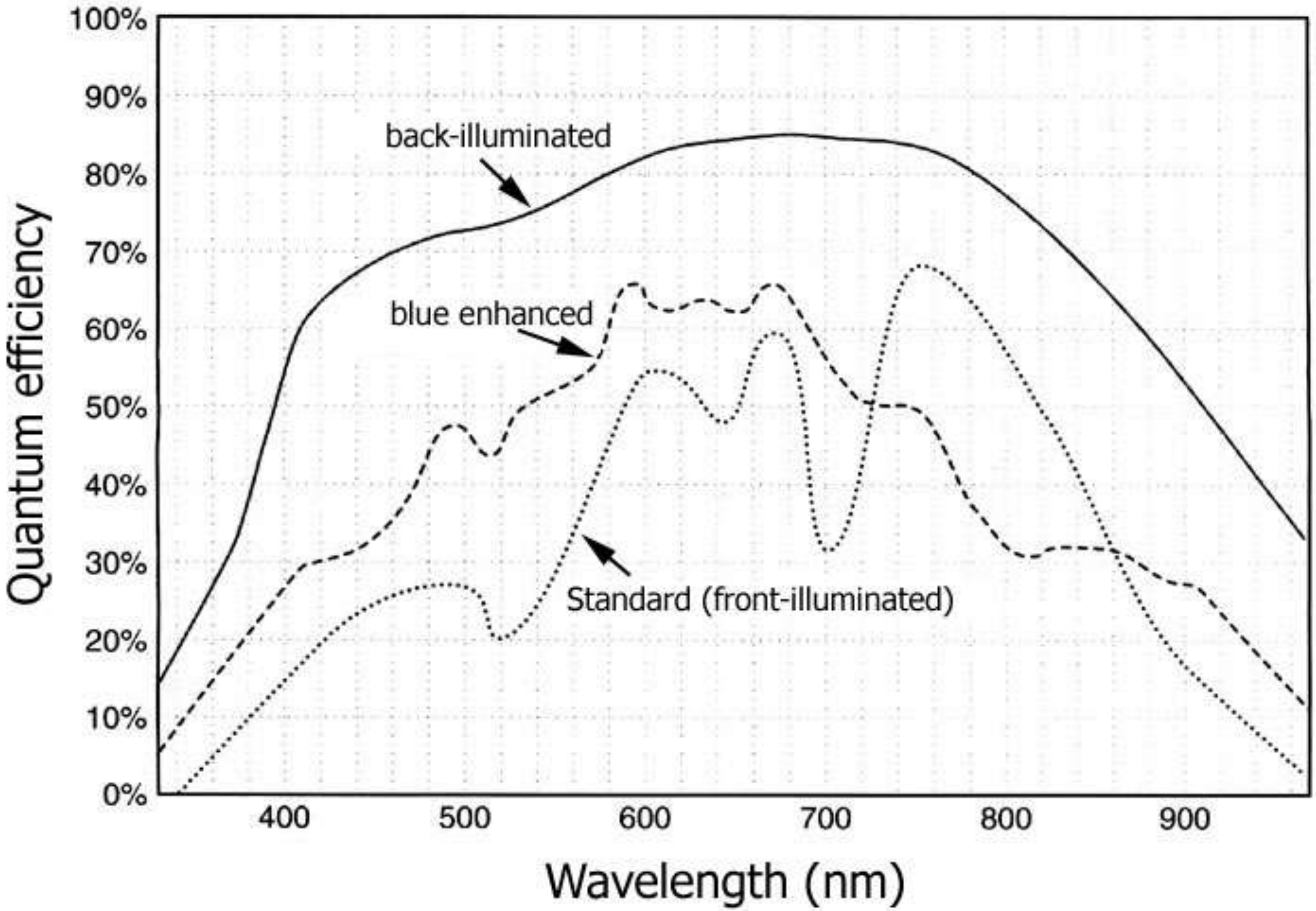
A.Cidadão

CCD detectors have high **QUANTUM EFFICIENCY** (they can record up to 90% of the photons that strike them) and exhibit a very good **LINEARITY** (their *output is almost directly proportional to the number of incident photons-* there is no reciprocity failure as found in long exposure emulsion based astrophotography). Images of deep-sky objects can be obtained in a few minutes and the output can be processed using standard image processing techniques.

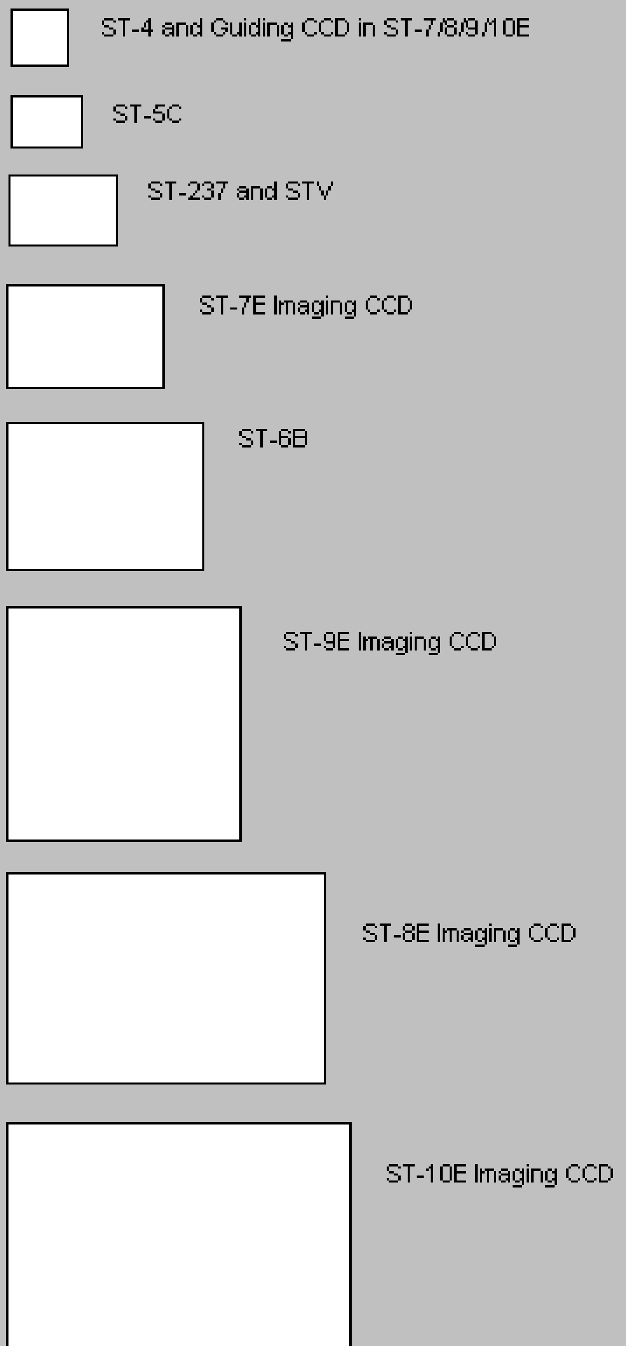


The **QUANTUM EFFICIENCY** of a sensor describes its response to different wavelengths of light. **STANDARD** front-illuminated sensors are more sensitive to green, red, and infrared wavelengths (in the 500 to 800 nm range) than they are to blue wavelengths (400 - 500 nm). **BACK-ILLUMINATED** CCDs have exceptional quantum efficiency compared to front-illuminated CCDs.

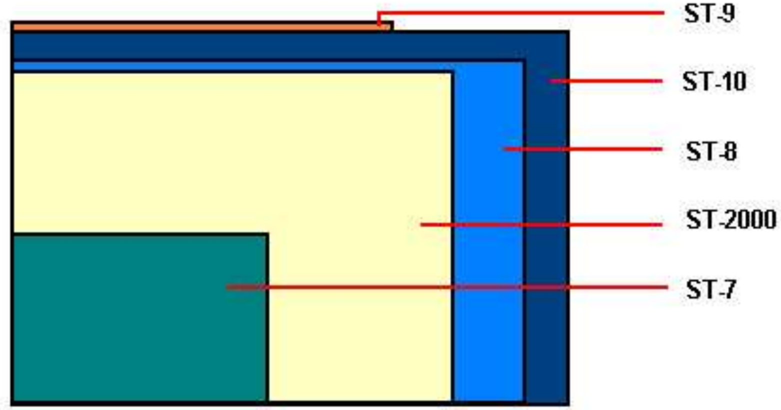




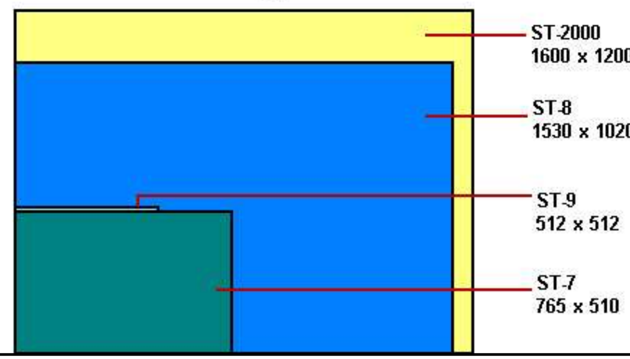
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Quantum efficiency
back-illuminated
blue enhanced
Standard (front-illuminated)
400
500
600
700
800
900
Wavelength (nm)



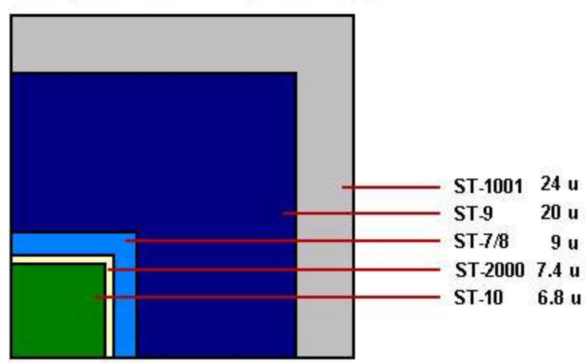
Relative CCD Sizes



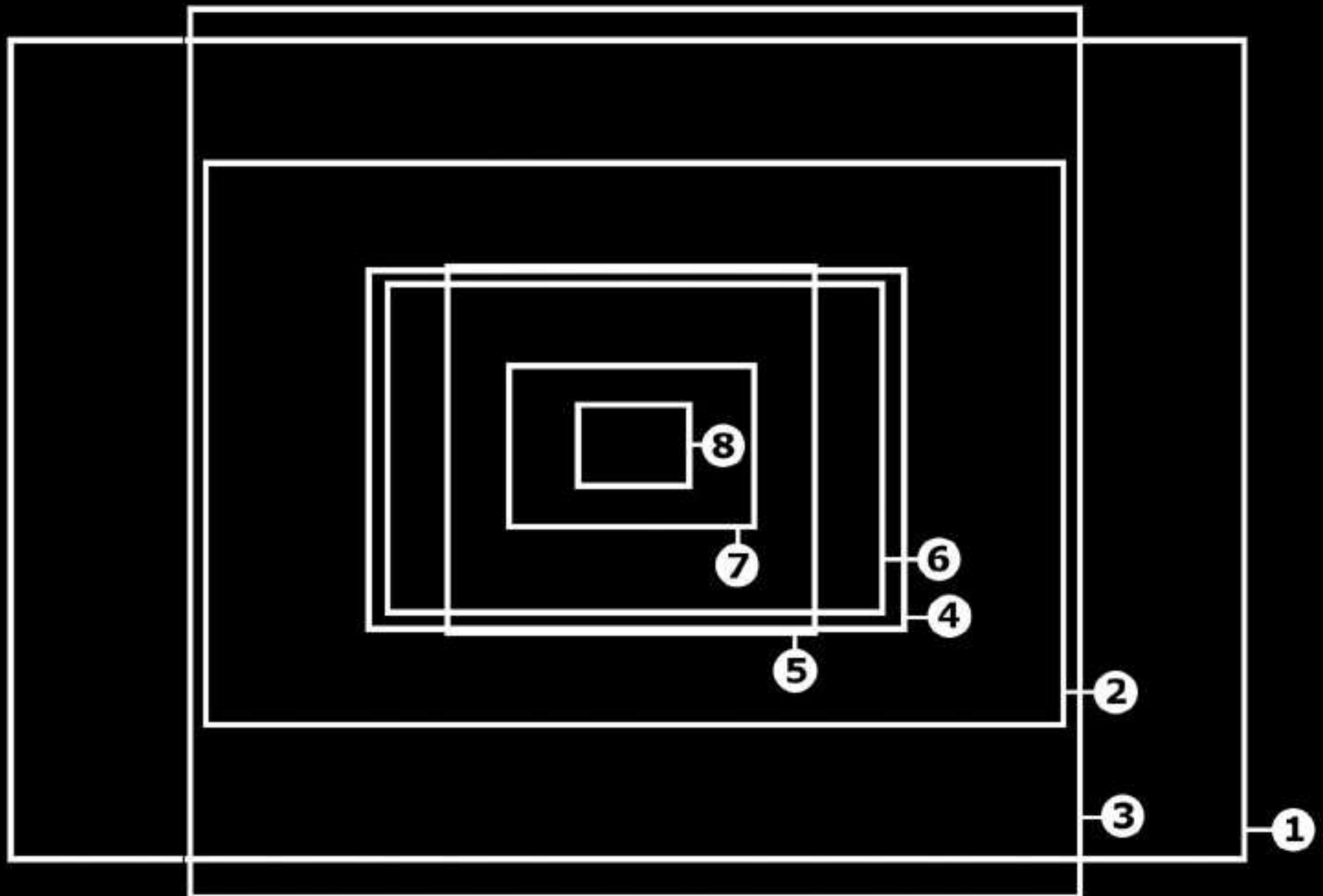
Relative Image Sizes



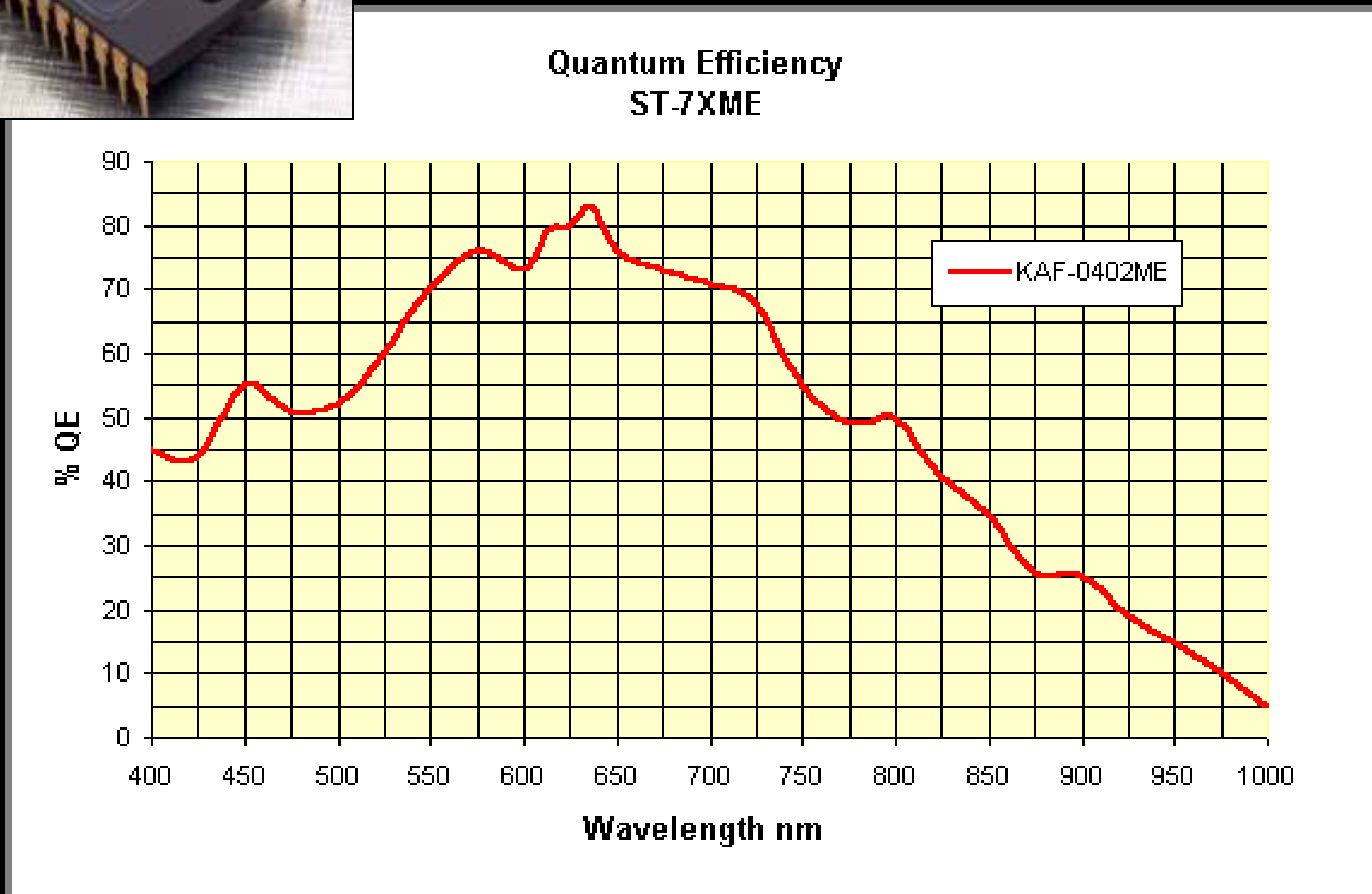
Relative Pixel Sizes



Relative sizes of KAF-1602E and KAF-1001E

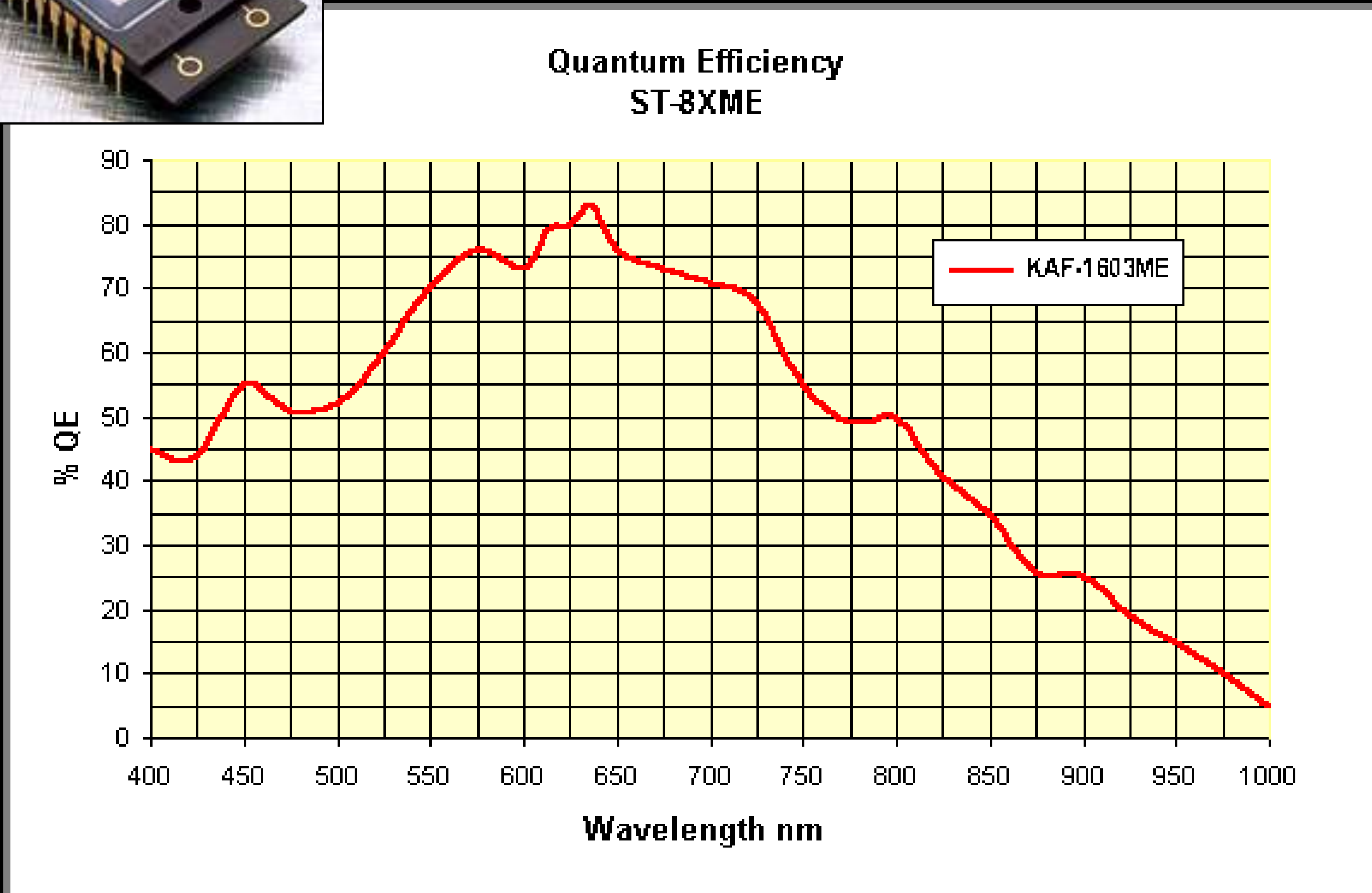


1- 35 mm, 2- FujiFilm S1, 3- SBIG ST-1001E, 4- SBIG ST-10E,
5- SBIG ST-9E, 6- SBIG ST-8E, 7- SBIG ST-7E, 8- SBIG ST-5C

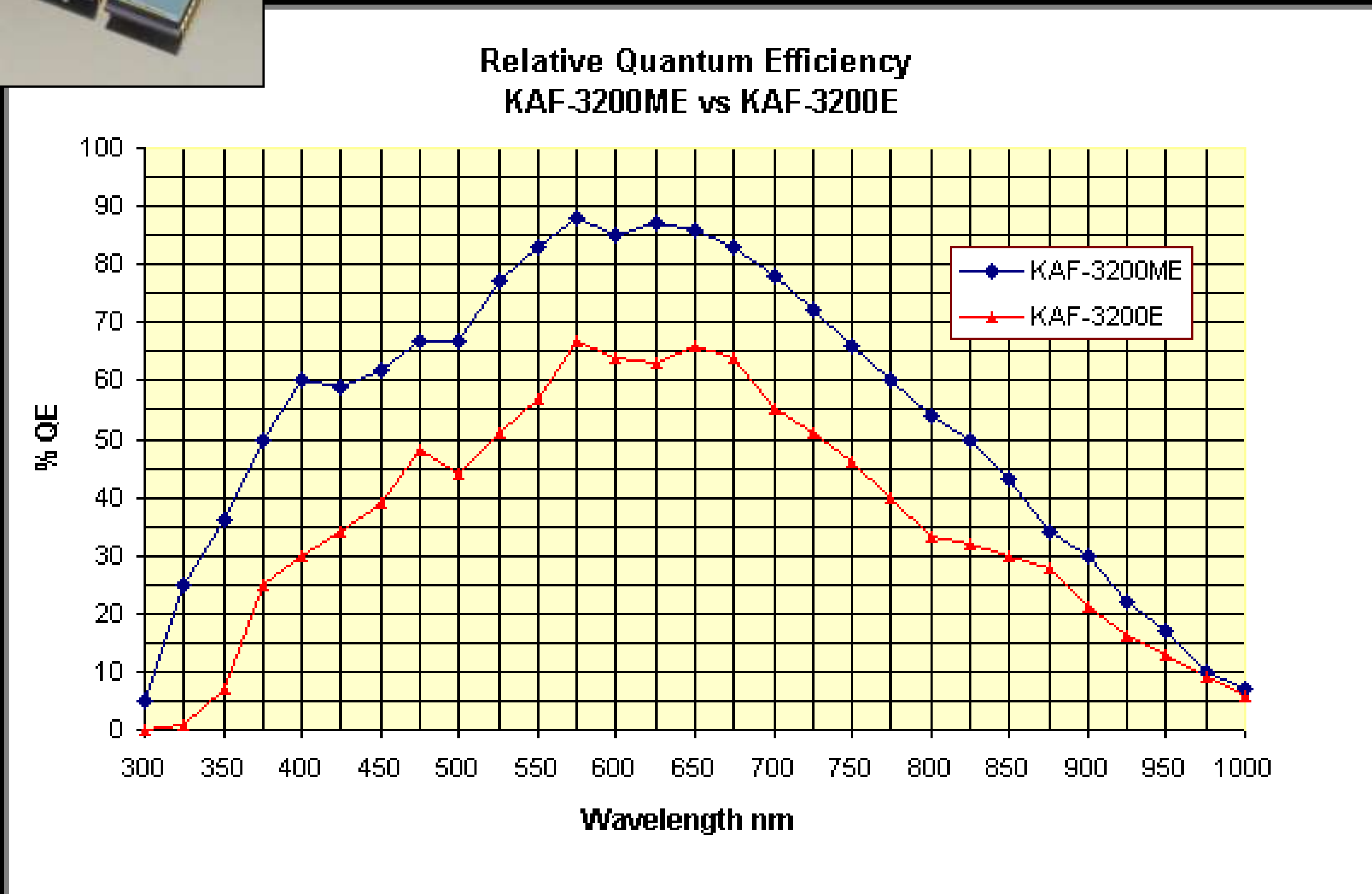


Quantum Efficiency
ST-7XME
% QE
90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
800
850
900
950
1000
Wavelength nm
KAF-0402ME

SBIG ST-7

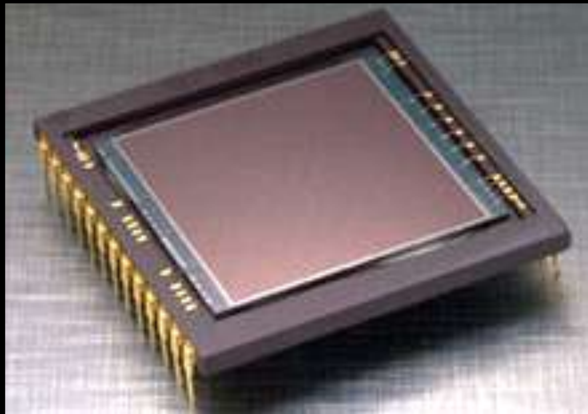

Quantum Efficiency
ST-8XME
KAF-1603ME
% QE
0
10
20
30
40
50
60
70
80
90
400
450
500
550
600
650
700
750
800
850
900
950
1000
Wavelength nm

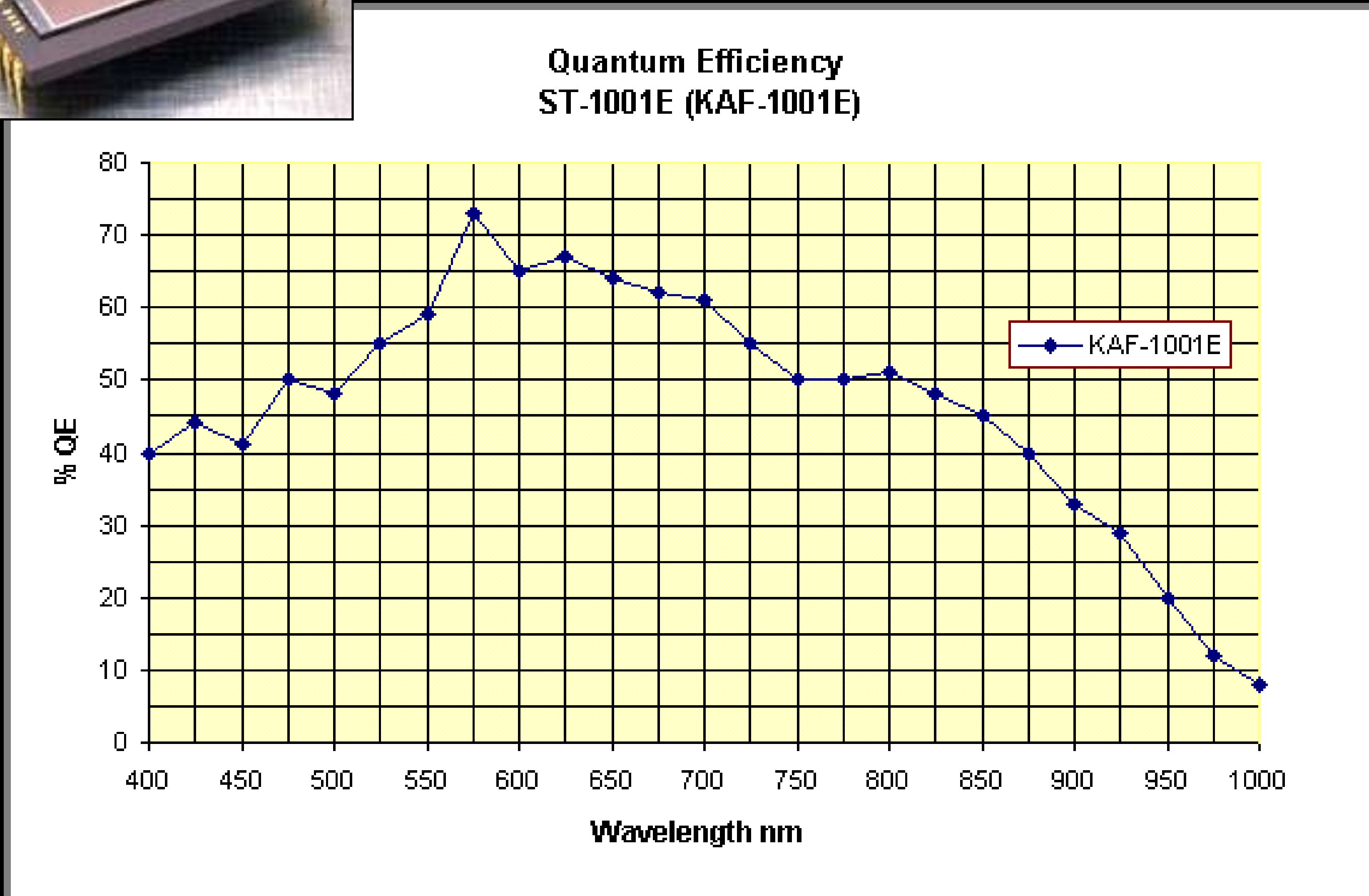
SBIG ST-8



Relative Quantum Efficiency
KAF-3200ME vs KAF-3200E
% QE
Wavelength nm
KAF-3200ME
KAF-3200E
0
10
20
30
40
50
60
70
80
90
100
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000

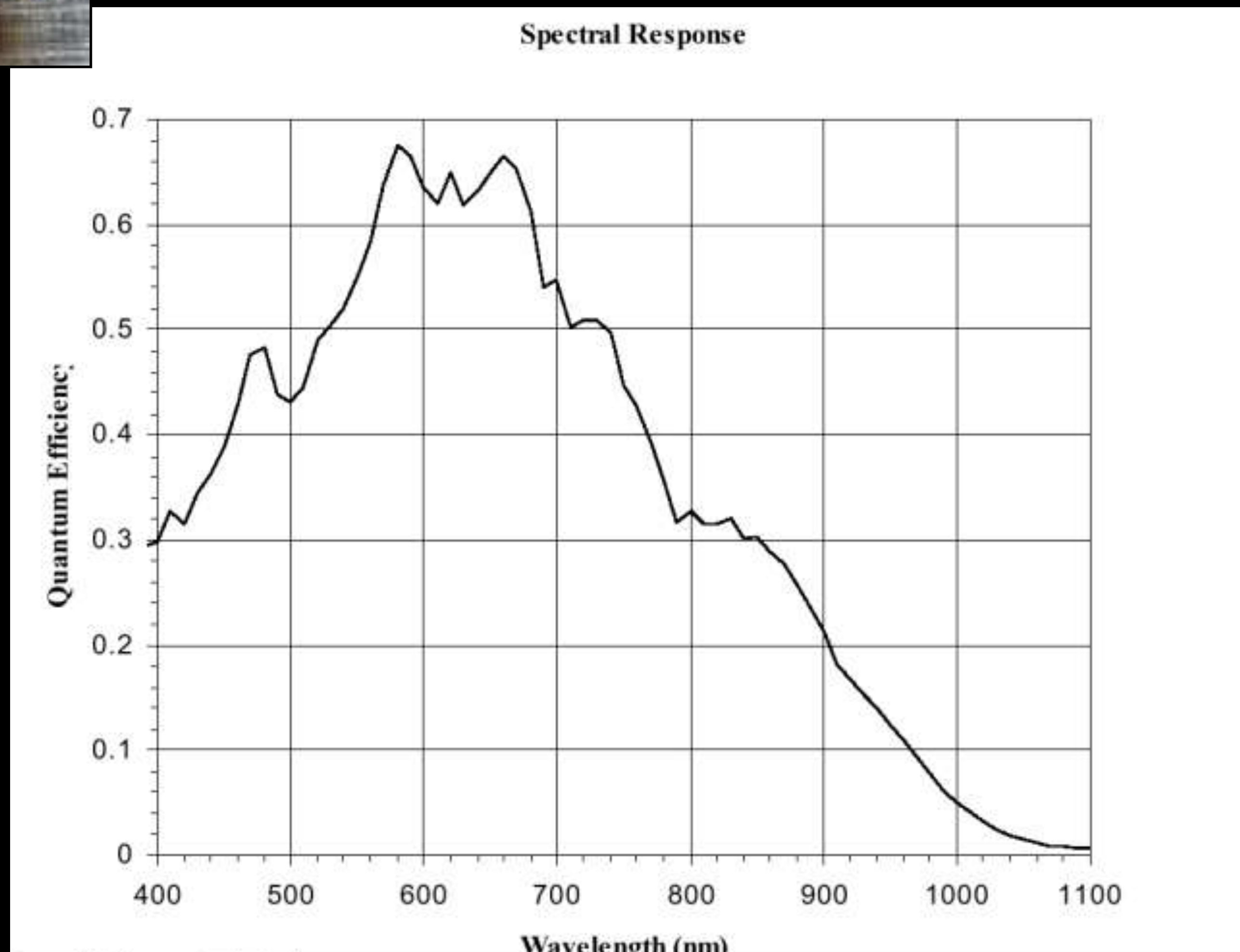
SBIG ST-10



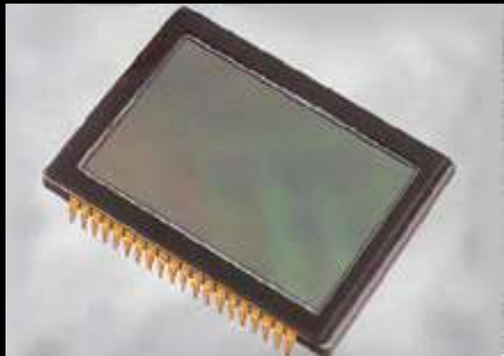


SBIG STL-1001

SBIG STL-6303



SBIG STL-11000



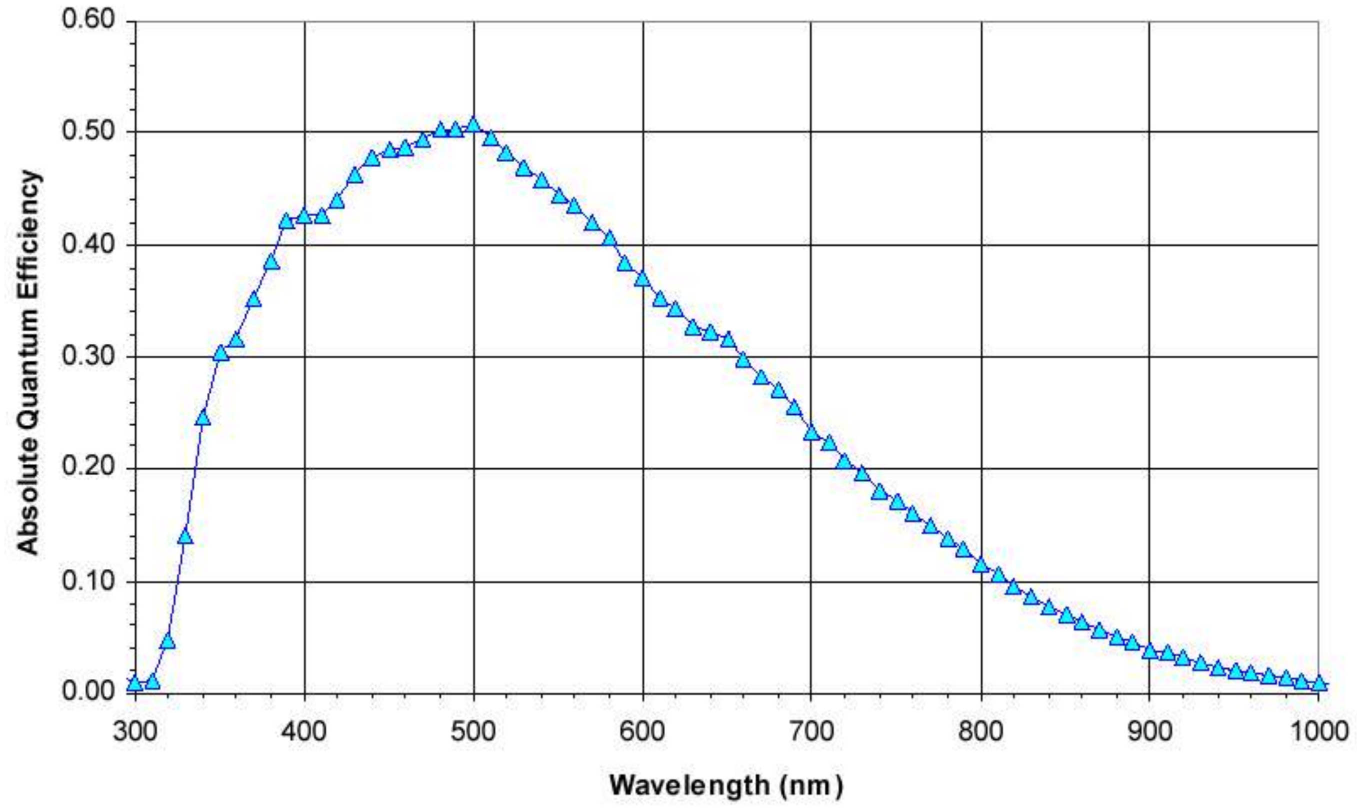


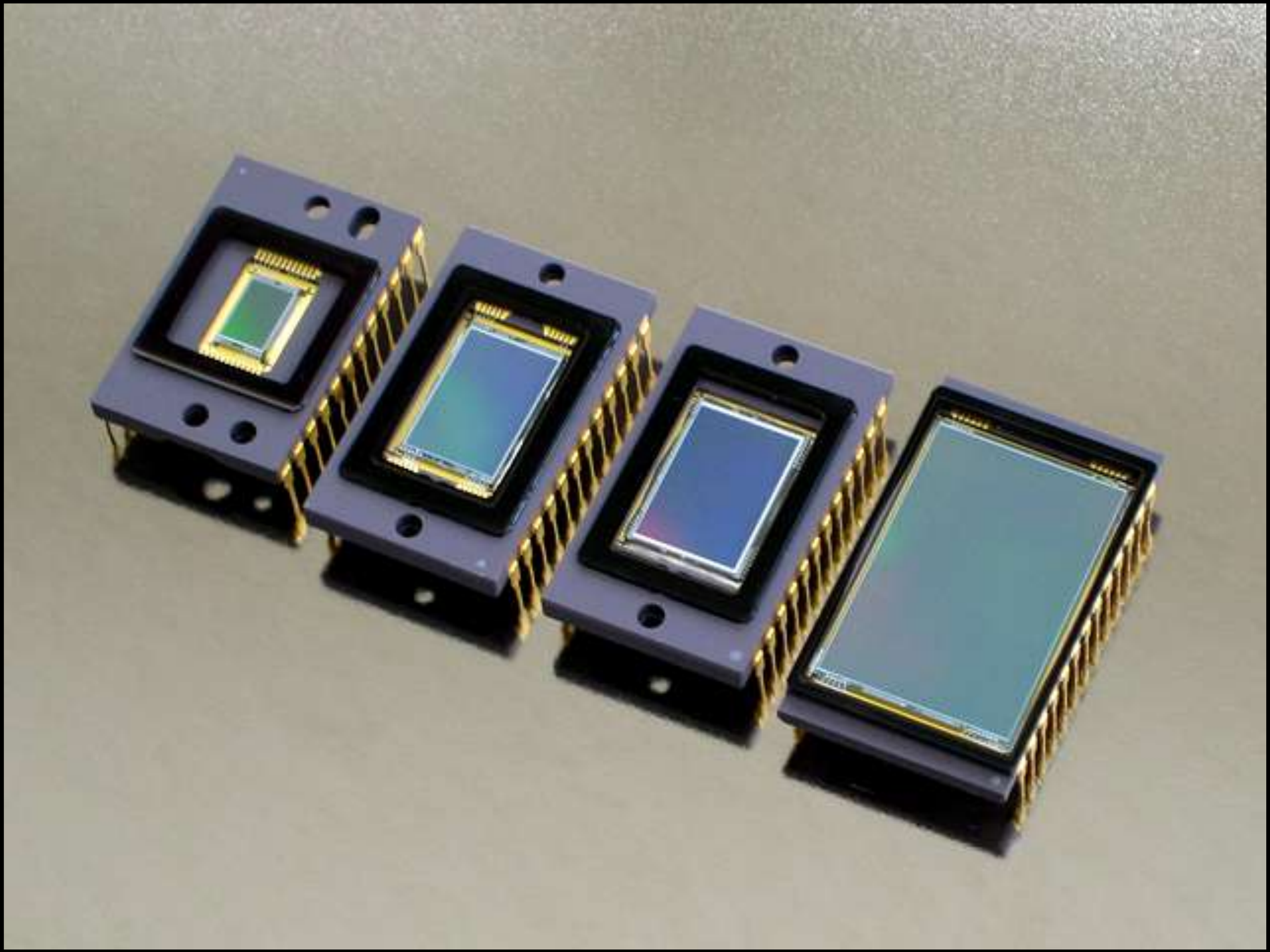
Figure 11 - Monochrome with Microlens Quantum Efficiency

CCD SPECIFICATIONS

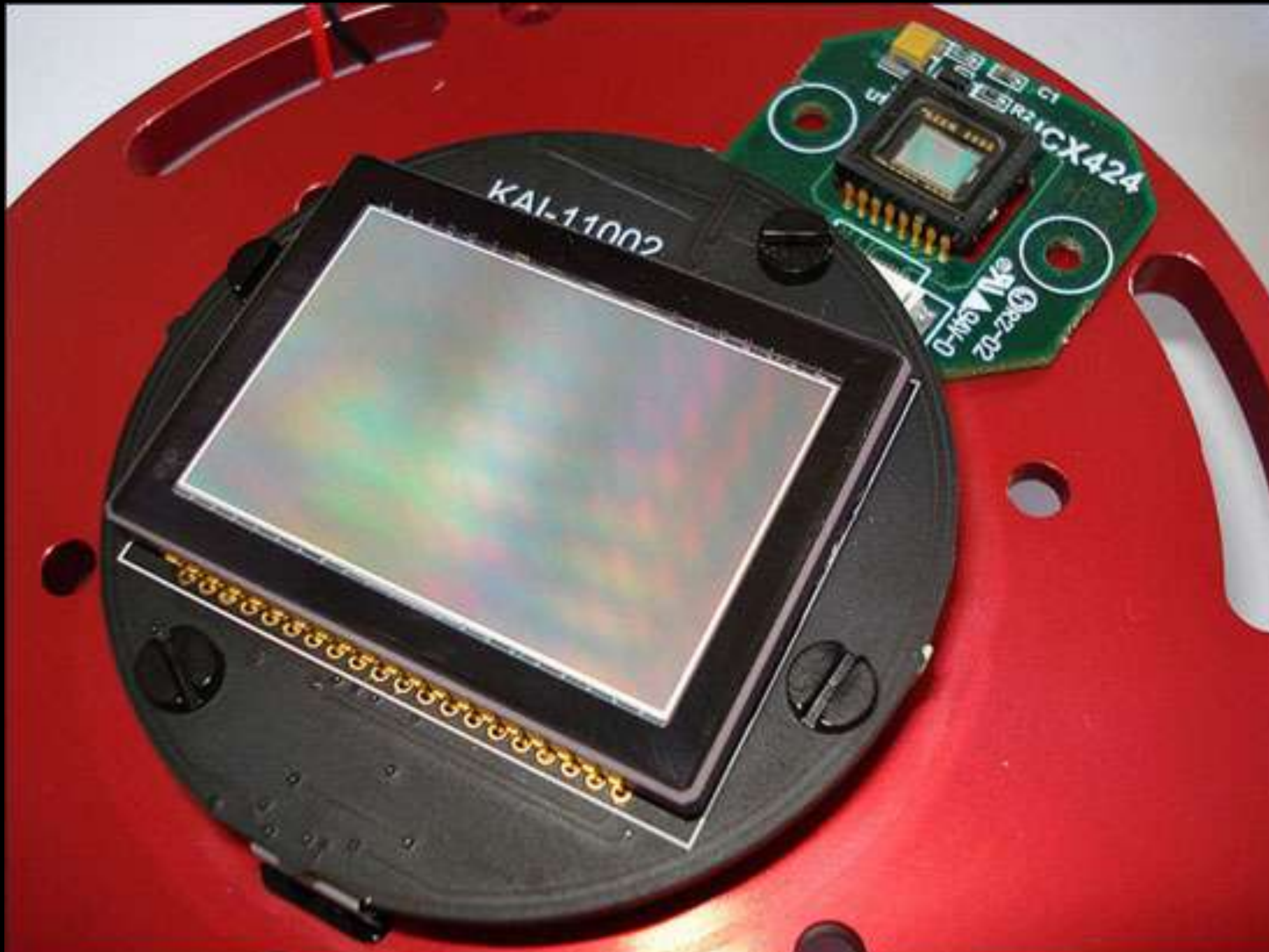
CCD	Kodak KAF-09000
Array Size (pixels)	3056 x 3056
Pixel Size	12 x 12 microns
Imaging Area	36.7 x 36.7 mm (1345 mm2)
Imaging Diagonal	51.9 mm
Video Imager Size	3.24"
Linear Full Well (typical)	110K electrons
Dynamic Range	84 dB
QE at 400 nm	37%
Peak QE (550 nm)	64%
Anti-blooming	>100X

CCD SENSITIVITY

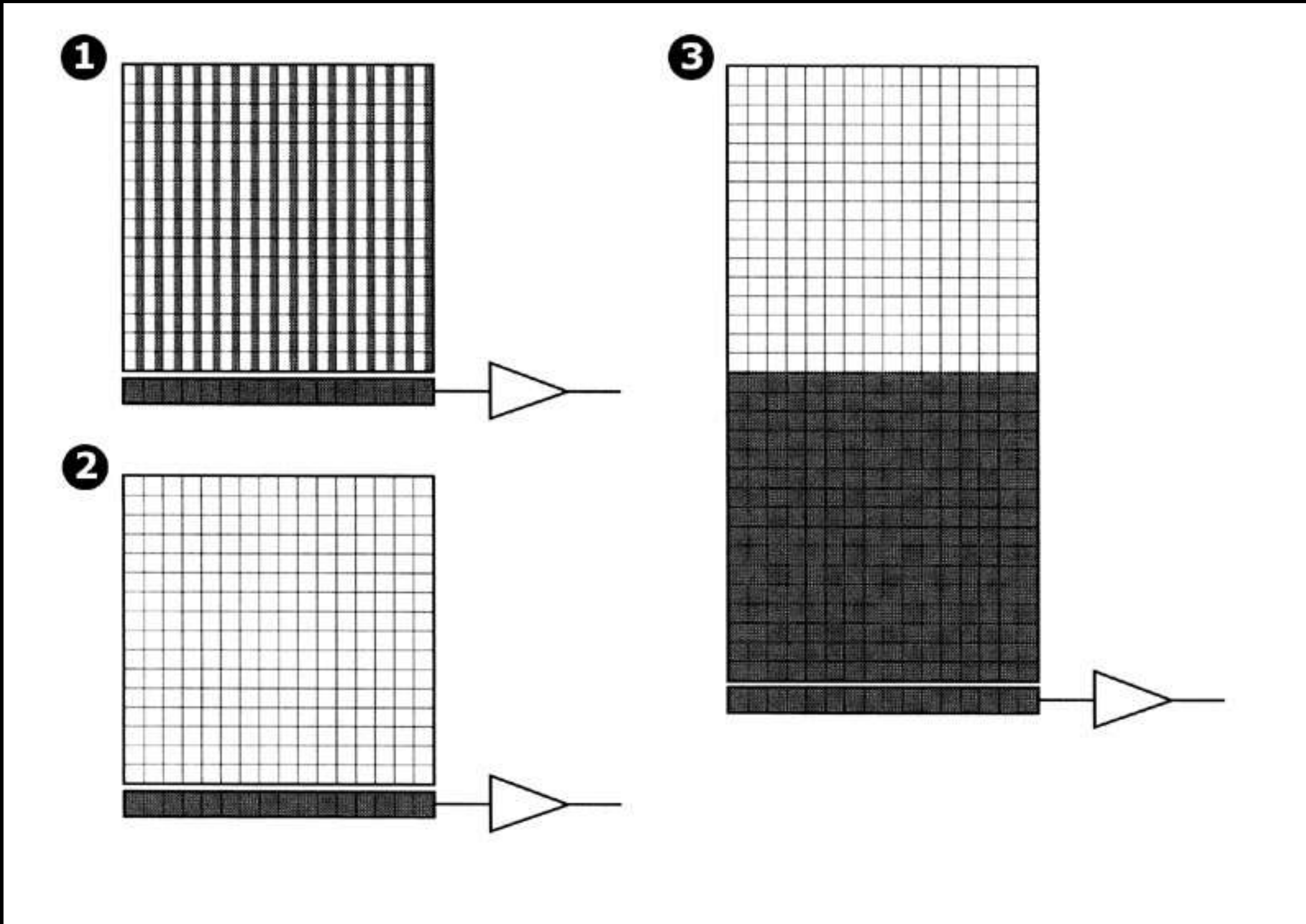
Alta U9000



Kodak Full Frame CCDs: KAF-0402ME, KAF-1603ME, KAF-3200ME and KAF-6303E



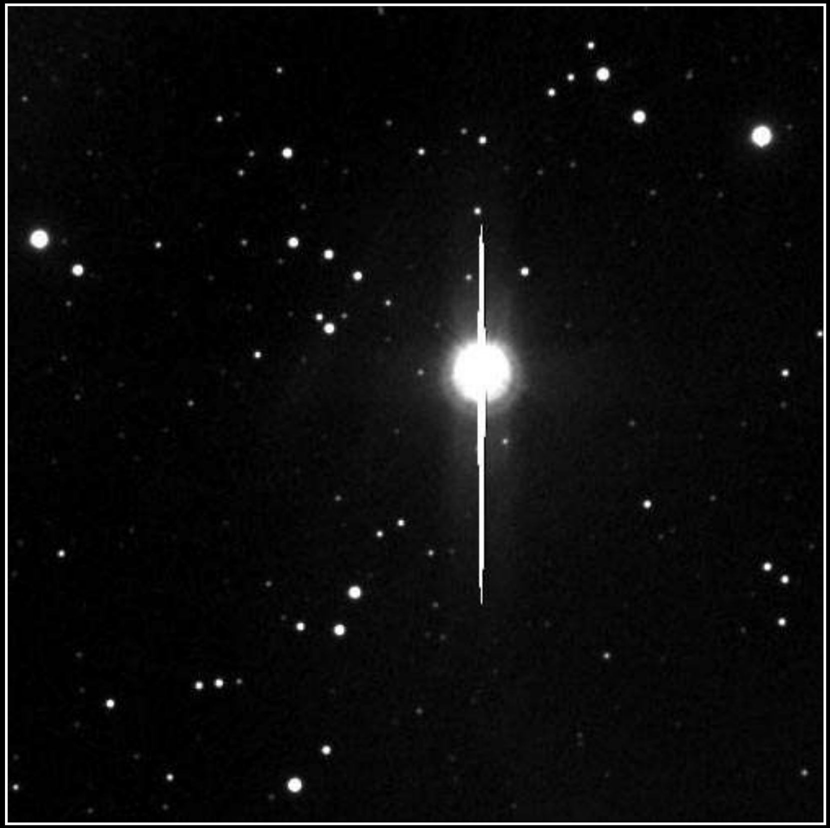
KAI-11002
ICX424

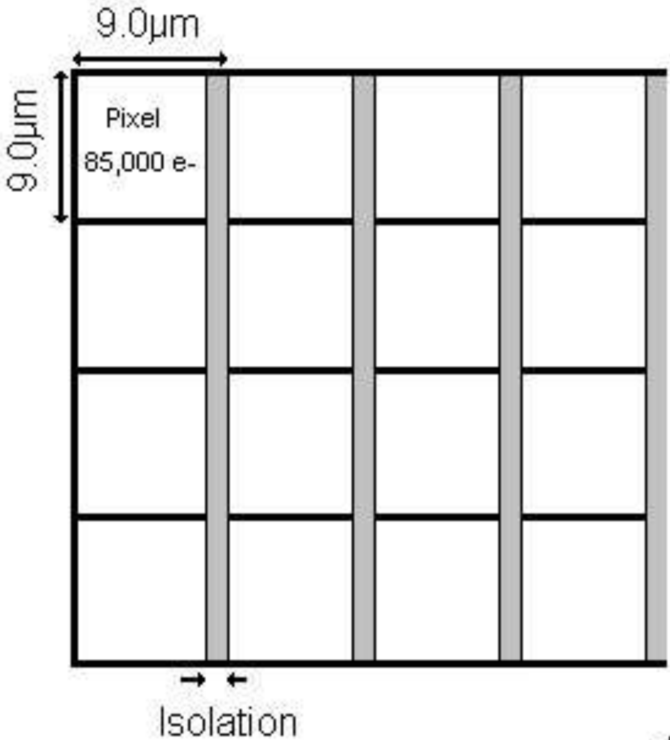


1-Interline-Transfer CCD, 2- Full-Frame CCD, 3- Frame-Transfer CCD

Some sensors have an **ANTI-BLOOMING GATE** designed to bleed off overflow from a saturated pixel. Without this feature, a bright star which has saturated the pixels will cause a vertical streak.

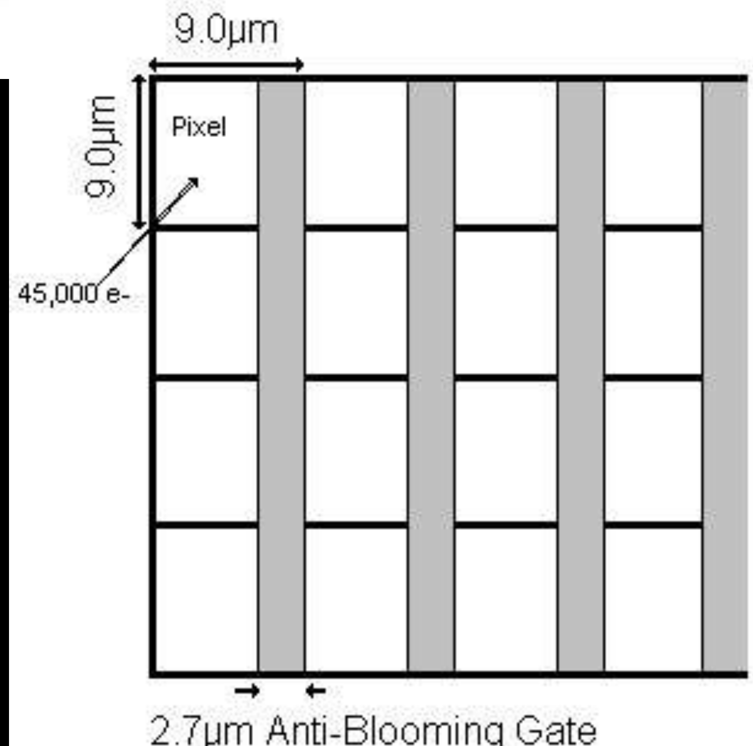
This anti-blooming gates built into the CCD occupy about 30% of the pixel area. The result is a 70% fill factor and reduced sensitivity and well depth. The reduced sensitivity means that you have to expose almost twice as long to get the same signal level as a CCD without the anti-blooming feature. Also, the area of the CCD occupied by the anti-blooming gate leaves a significant gap between pixels, reducing the effective resolution of the sensor.





No Anti-Blooming Gate

100% Fill Factor
85,000 electron well depth
Higher Quantum Efficiency
Blooming (Streaking) possible



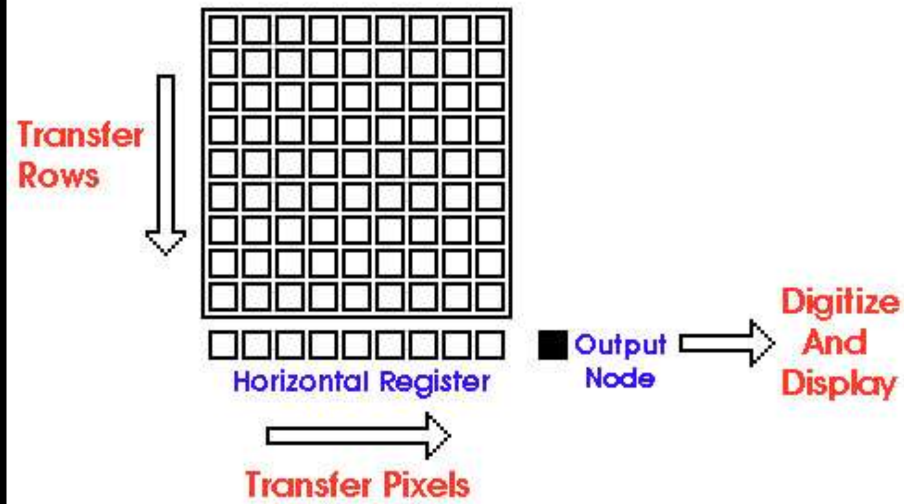
Anti-Blooming Gate

70% Fill Factor
45,000 electron well depth
Lower Quantum Efficiency

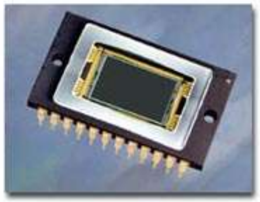
As light (photons) falls on the surface of the CCD, charge (electrons) accumulates in each pixel. The number of electrons that can accumulate in each pixel is referred to as **WELL DEPTH**. For the KAF-0400 and KAF-1600, this is 85,000 electrons.

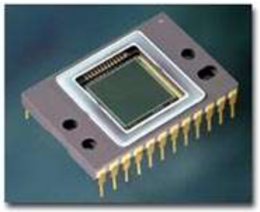
Some CCDs, such as the SITe 502AB have well depths exceeding 350,000 electrons. Once the exposure is complete, this charge must be transferred to a single output and digitized.

This is accomplished in two steps. First, an entire row is transferred in the vertical direction to the horizontal register. Second, charge is transferred horizontally in this register to the output amplifier.

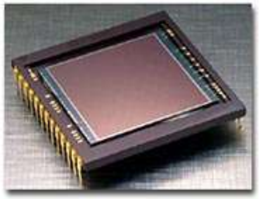


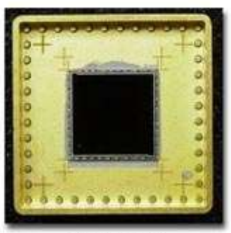

KAF-401E

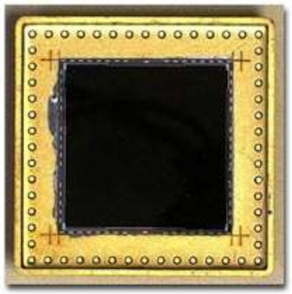

KAF-1602E


KAF-0261E


KAF-3200E

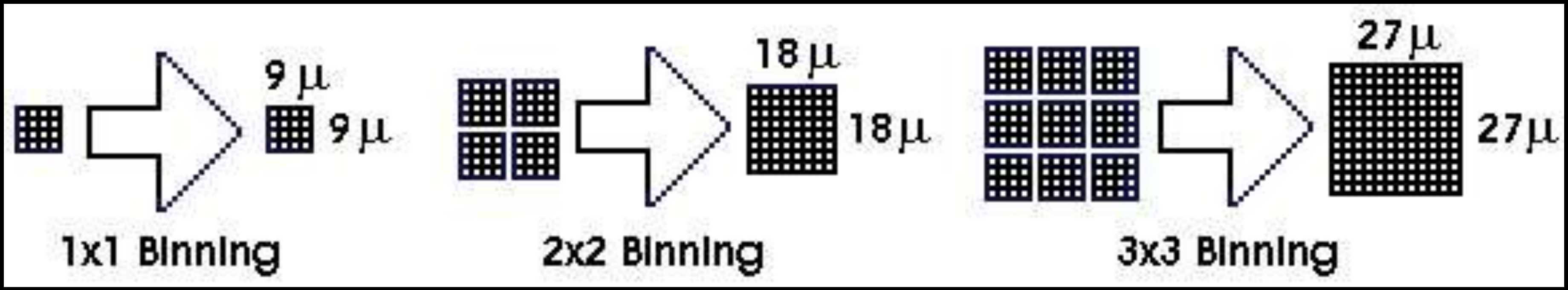

KAF-1001E

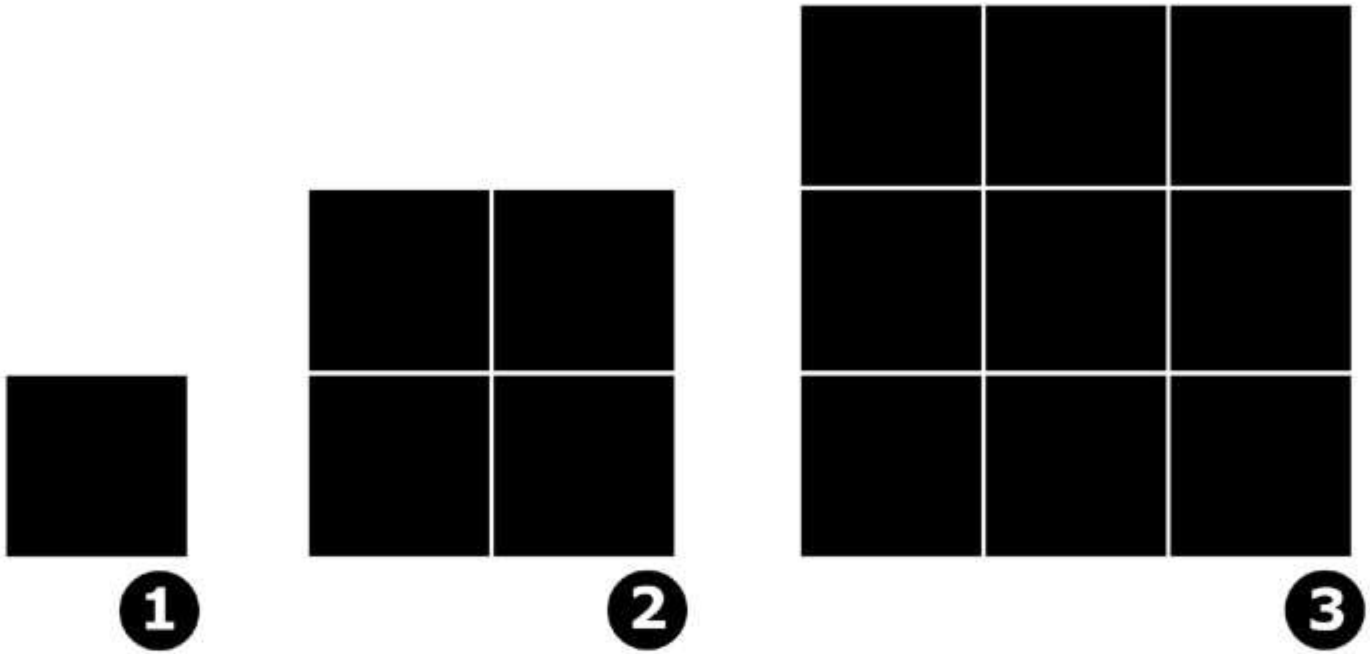

SI-032AB


SI-003AB

Most CCDs have the ability to clock multiple pixel charges in both the horizontal and vertical direction into a single larger charge or "SUPER PIXEL".This super pixel represents the area of all the individual pixels contributing to the charge. This is referred to as **BINNING**.

Binning of 1x1 means that the individual pixel is used as is. A binning of 2x2 means that an area of 4 adjacent pixels have been combined into one larger pixel, and so on. In the latter exemple the sensitivity to light has been increased by 4 times (the four pixel contributions), but the resolution of the image has been cut in half.




1
2
3

System **GAIN**, is a way of expressing how many electrons of charge are represented by each count (ADU). A gain of 2.5 electrons/ADU indicates that each count or gray level represents 2.5 electrons. This implies that the total well depth (85,000 electrons) of a Kodak KAF-0400 pixel could be represented in 85000/2.5=34000 counts.

As long as the total well depth of a sensor can be represented, a lower gain is better to minimize the noise contribution from the electronics and give better resolution. Gains which are unnecessarily high can result in more digitization noise, while gains which are too low will minimize noise at the expense of well depth. For example, a gain of 1.0 would certainly minimize the electronics contribution to noise, but would only allow 65,536/1.0 = 65,536 electrons of the 85,000 to be digitized.

SYSTEM GAINS are designed as a balance between digitization counts, digitization noise, and total well depth.

dynamic range of a CCD image sensor

The dynamic range (DR) is defined as the ratio of the maximum possible signal (full well capacity), versus the total noise signal (in the dark). The data is expressed in decibels [dB] or is dimensionless:

$$DR_{CCD} = \frac{\text{full well capacity}}{\text{rms noise}_{\text{dark}}}$$

$$DR_{CCD} = 20 \cdot \log\left(\frac{\text{full well capacity}}{\text{rms noise}_{\text{dark}}}\right) \text{ [dB]}$$

common commercial CCD image sensor specifications

	Sony ICX 285	Kodak KAI-1020	Kodak KAI-11000
full well cap. [e^-]	18.000	40.000	60.000
noise rms [e^-]	6	10-15	12-14
dynamic range [x/1]	3000:1	3200:1	5000:1
dynamic range [dB]	73.1	70.1	74.0

DIGITIZATION, also referred to as analog to digital (A/D) conversion, is the process by which charge from the CCD is translated into a binary form used by the computer. The term binary refers to the base 2 number system used. A 12 bit camera system will output 2 raised to the 12th power or 4096 levels. A 16 bit camera will output 2 raised to the 16th power or 65536 levels.

resolution [bit] $x \Rightarrow 2^x$	dynamic range of analog-to-digital conversion [digitizing steps]	dynamic range of analog-to-digital conversion [dB]
8	256	48.2
10	1024	60.2
12	4096	72.3
14	16384	84.3
16	65536	96.3

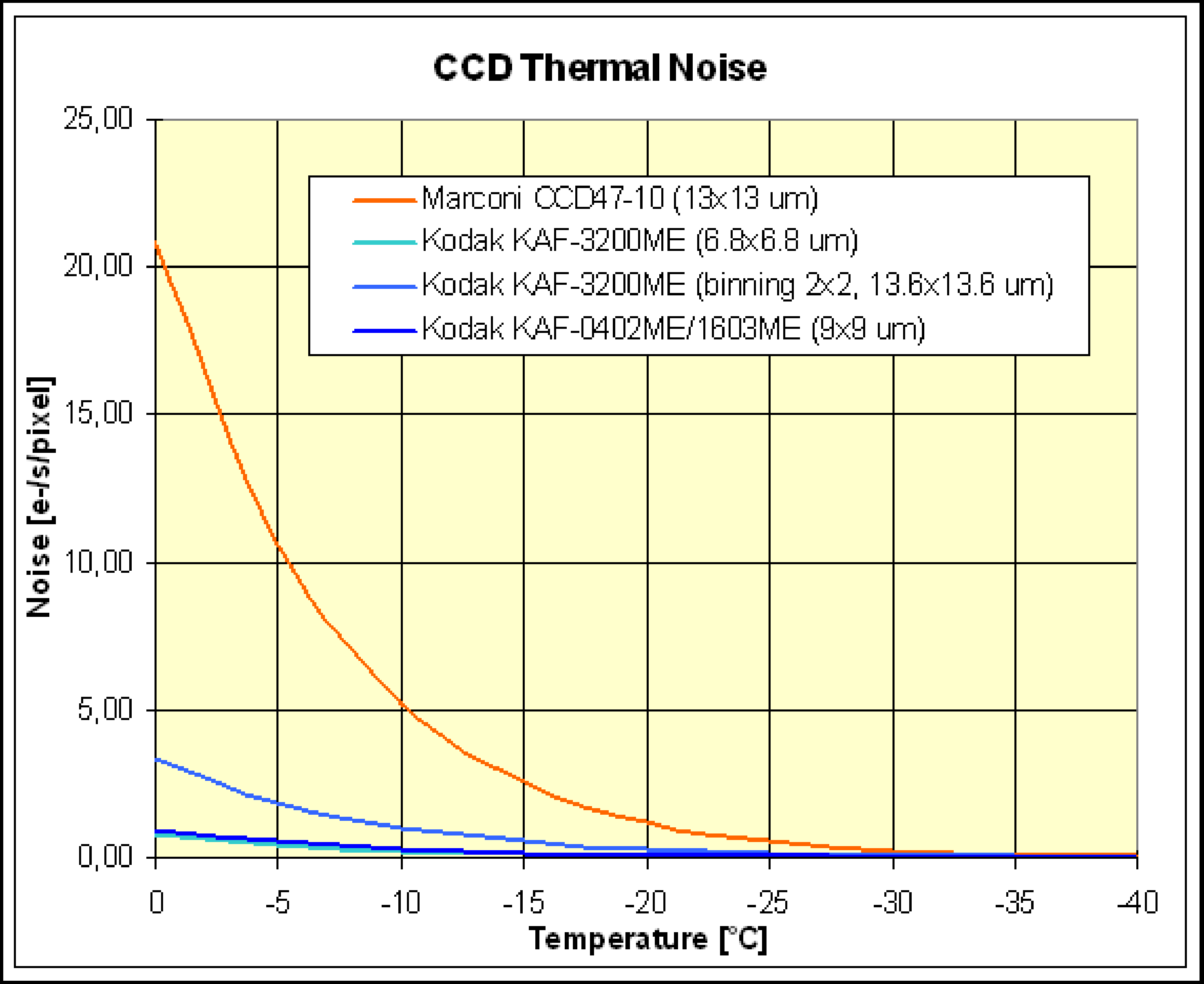
Long exposure deep-sky images obtained with a CCD are always distorted by several of **DEFECTS**:

During the exposure, a **THERMAL INTERFERENCE SIGNAL** builds up in each pixel. The CCD needs to be cooled to a cryogenic temperature (100 K, or -173 °C) to reduce this signal to a negligible level. Unfortunately, most CCD cameras suffer from the effect of this signal when they are only slightly cooled (temperature over -50 °C). The principal consequence of the dark current is noise on the image.

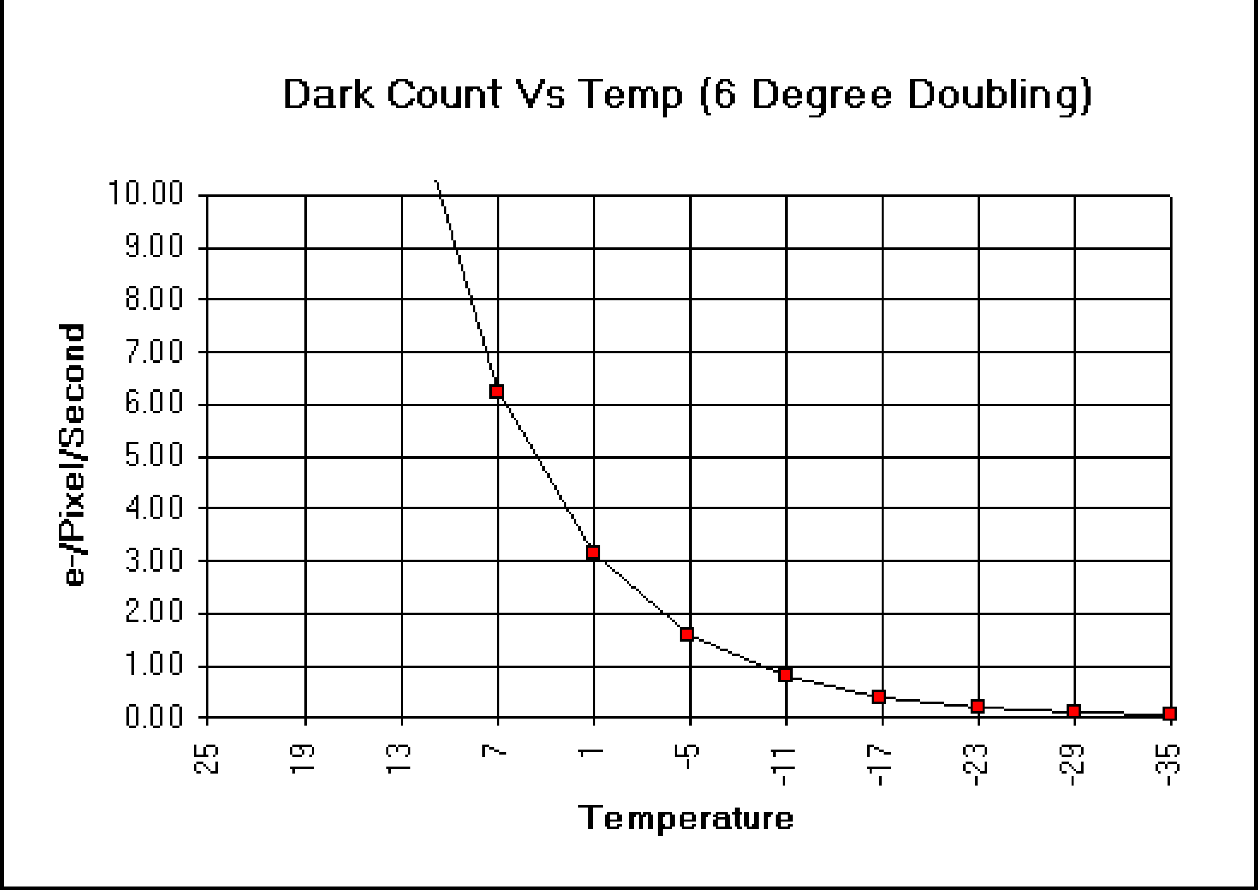
This noise has two origins:

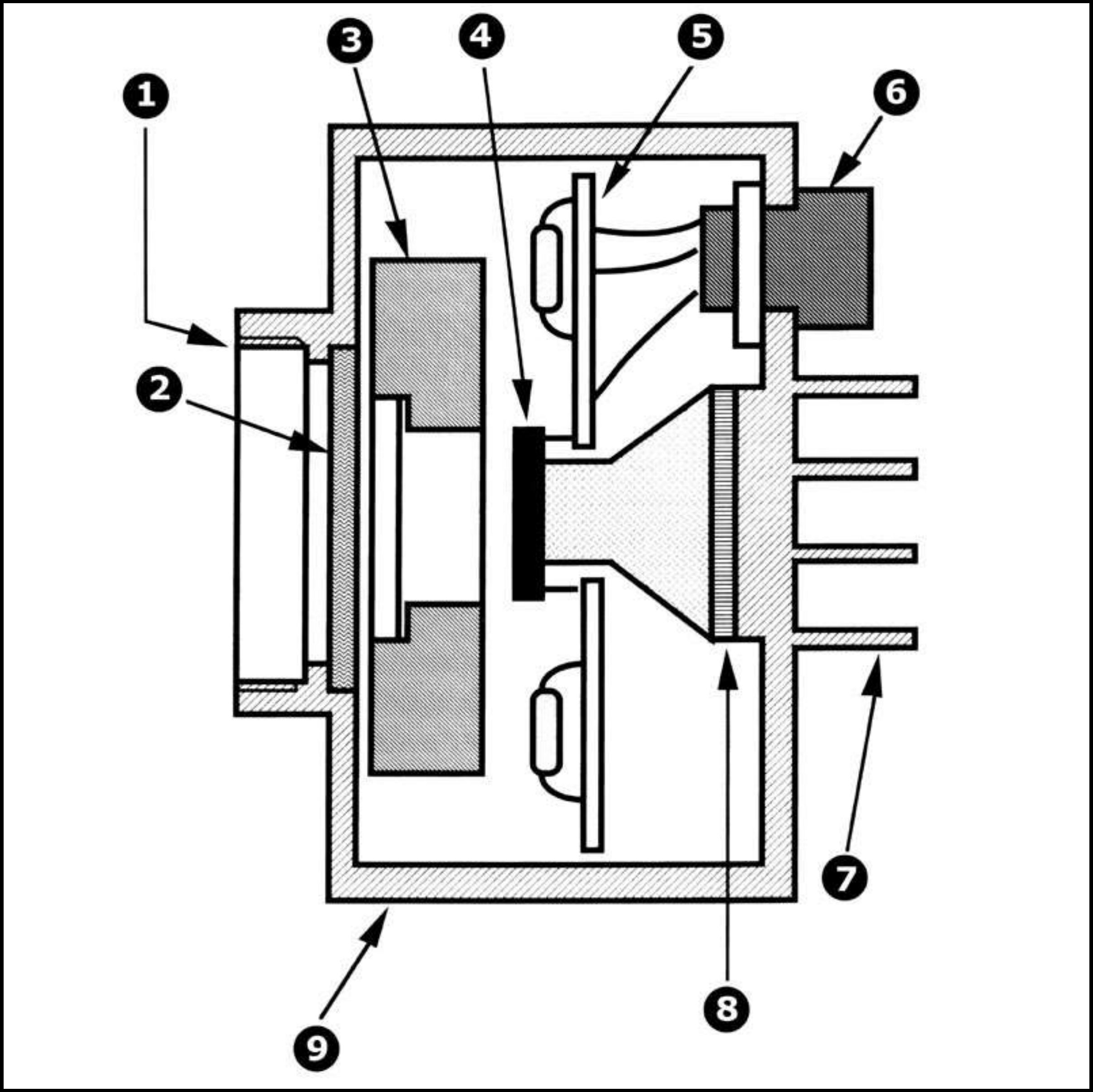
• **READING NOISE** linked to instantaneous fluctuations when the information from each pixel of the CCD is read. The only simple way to reduce this noise is to acquire several images of the same object and then average them;

• **SPATIAL NOISE** due to the fact that each pixel in the image reacts differently to the dark current, which gives a grainy aspect to the raw image. This difference in sensitivity to the dark current is strongly correlated from one image to another, so it is possible to produce a reference map of the interference signal to correct the images. The dark current map is obtained by the accumulation of many (typically 7 to 10) long exposure images taken in complete darkness. The CCD should be cooled as usual to reduce the reading noise.

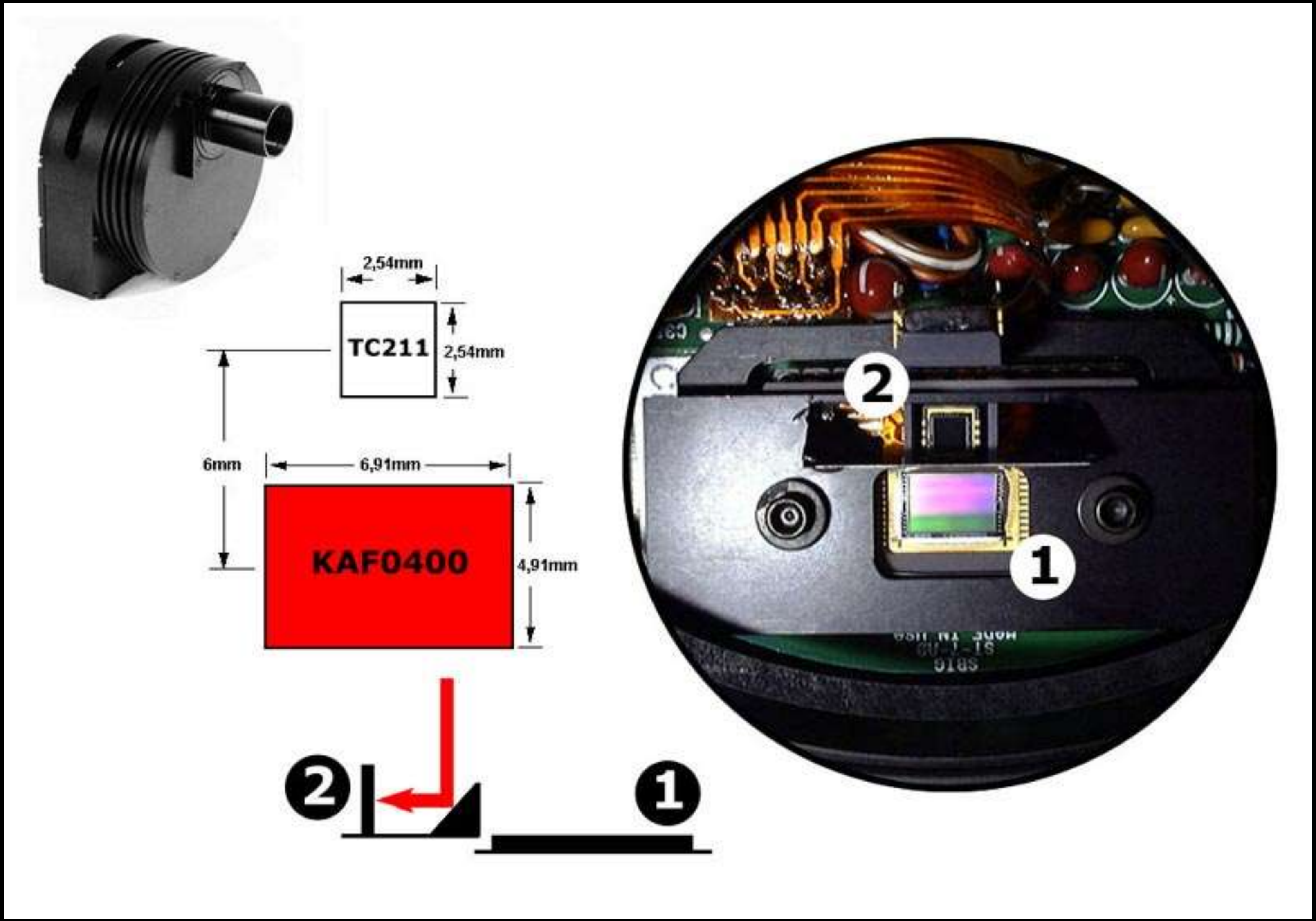

CCD Thermal Noise
Marconi CCD47-10 (13x13 um)
Kodak KAF-3200ME (6.8x6.8 um)
Kodak KAF-3200ME (binning 2x2, 13.6x13.6 um)
Kodak KAF-0402ME/1603ME (9x9 um)
Noise [e-/s/pixel]
25,00
20,00
15,00
10,00
5,00
0,00
0
-5
-10
-15
-20
-25
-30
-35
-40
Temperature [°C]

Next to the quantum efficiency, resolution (number of bits) and noise figure, **DARK COUNT** is perhaps the most important CCD specification. Dark count refers to the property of all CCD sensors to generate charge in each pixel on its own with time and depending on the temperature. The lower the temperature of the sensor, the lower the dark count.

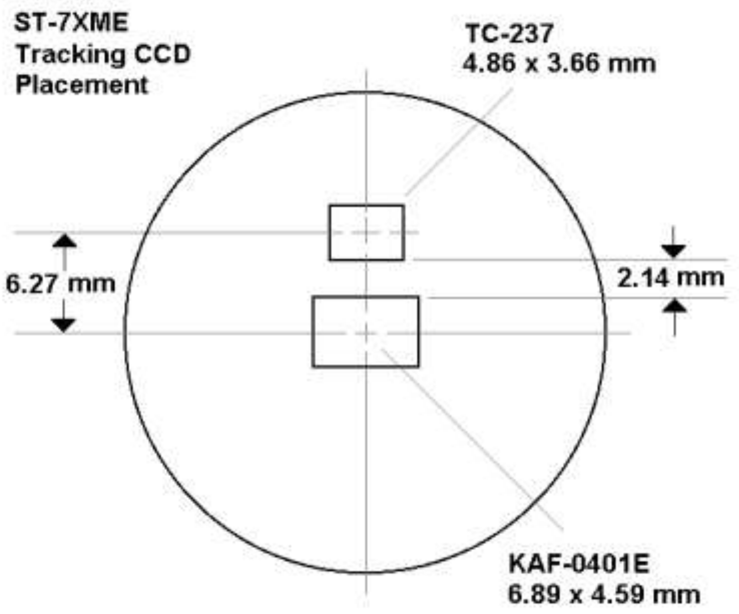


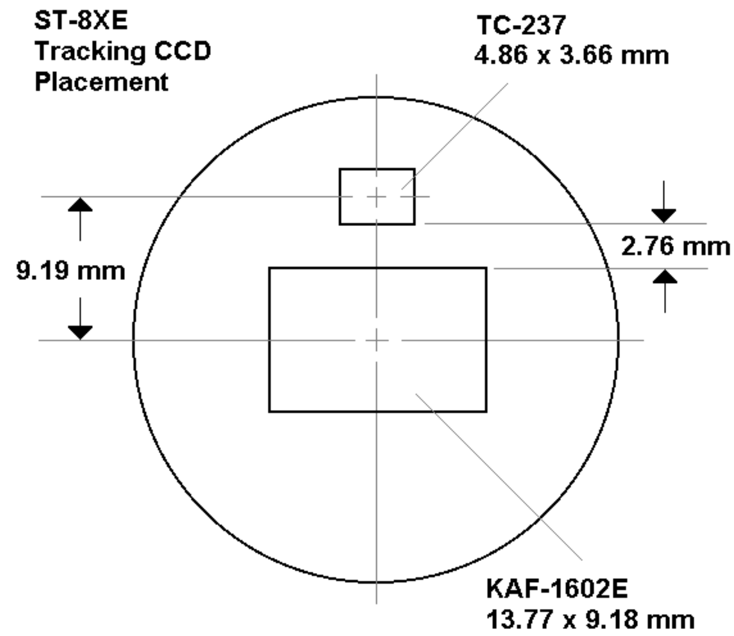


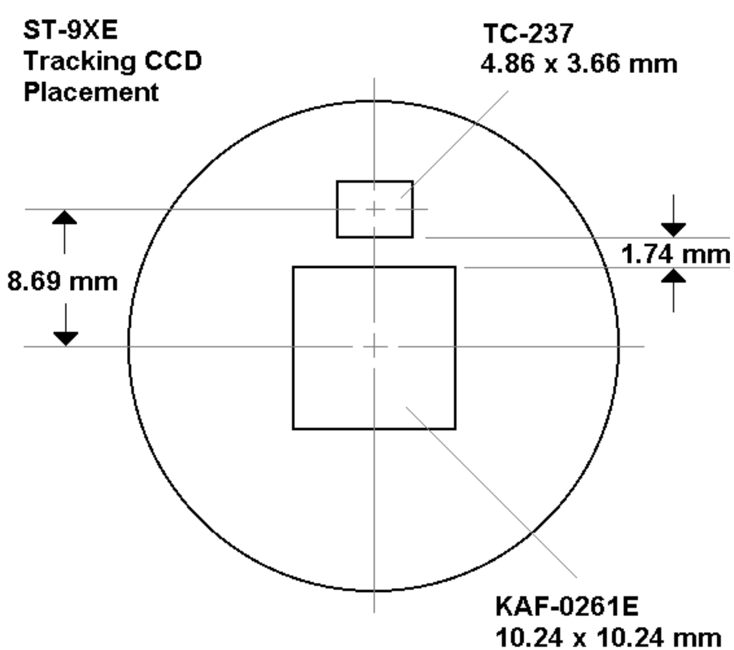
Anatomy of a CCD camera: 1- Adapter (M42); 2- Optical window; 3- Mechanical shutter; 4- CCD detector; 5- Amplifier; 6- Power connection; 7- Dissipator; 8- Peltier (cooling); 9- Housing.

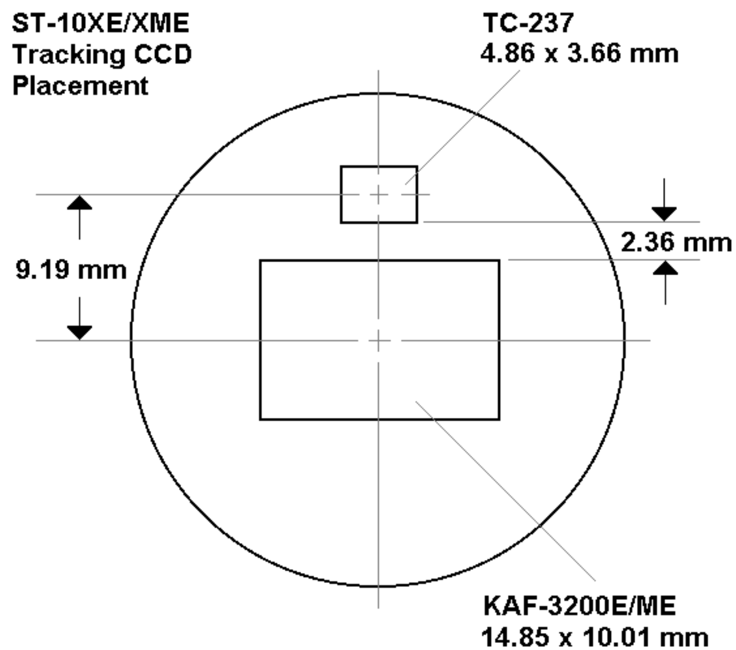


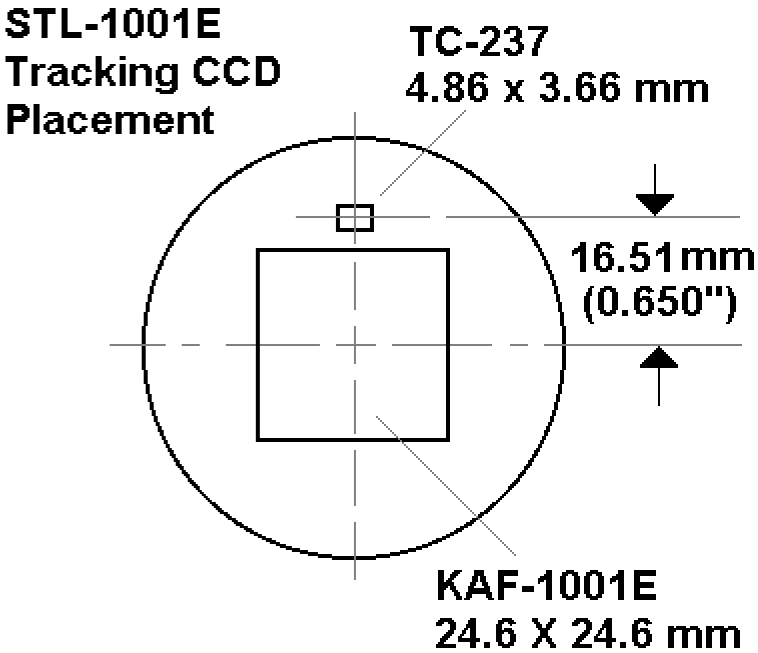
Layout of the imaging and guiding detectors, SBIG ST-7

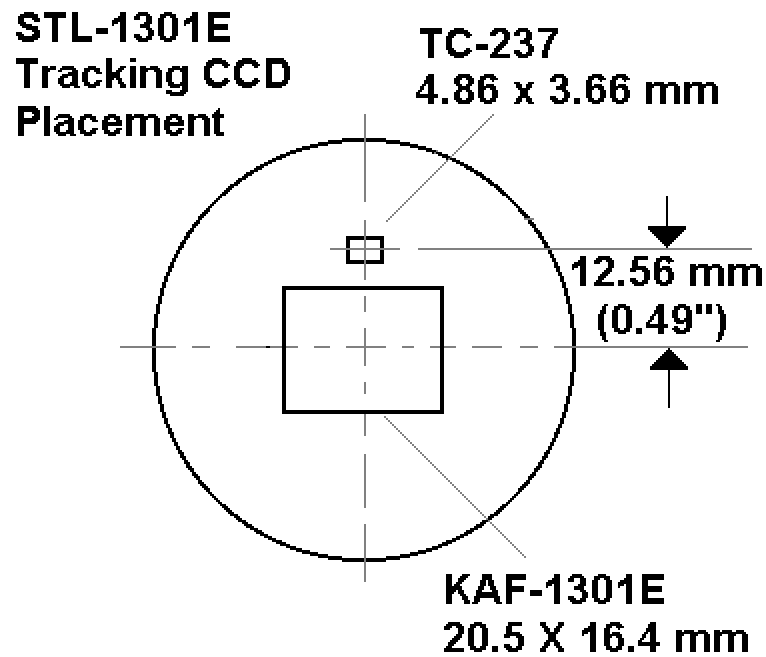

ST-7XME
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
6.27 mm
2.14 mm
KAF-0401E
6.89 x 4.59 mm

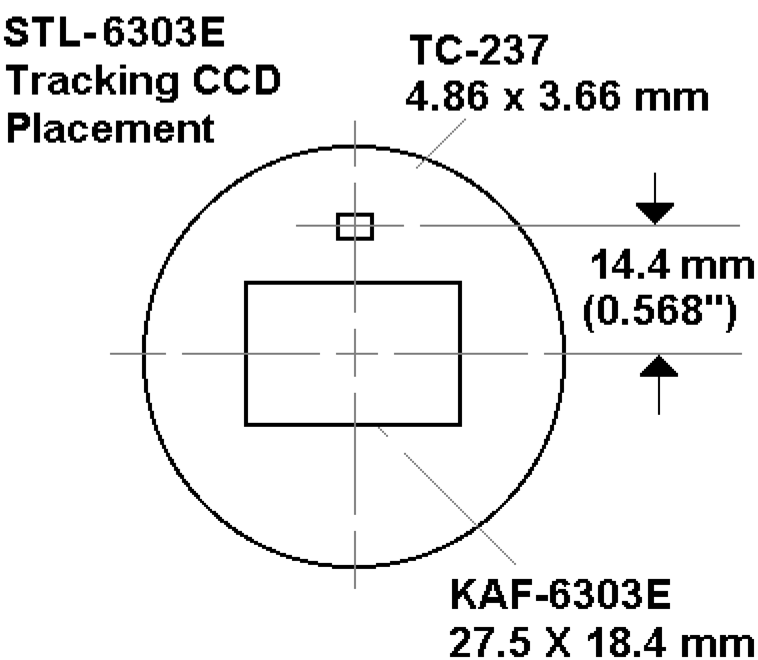

ST-8XE
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
9.19 mm
2.76 mm
KAF-1602E
13.77 x 9.18 mm

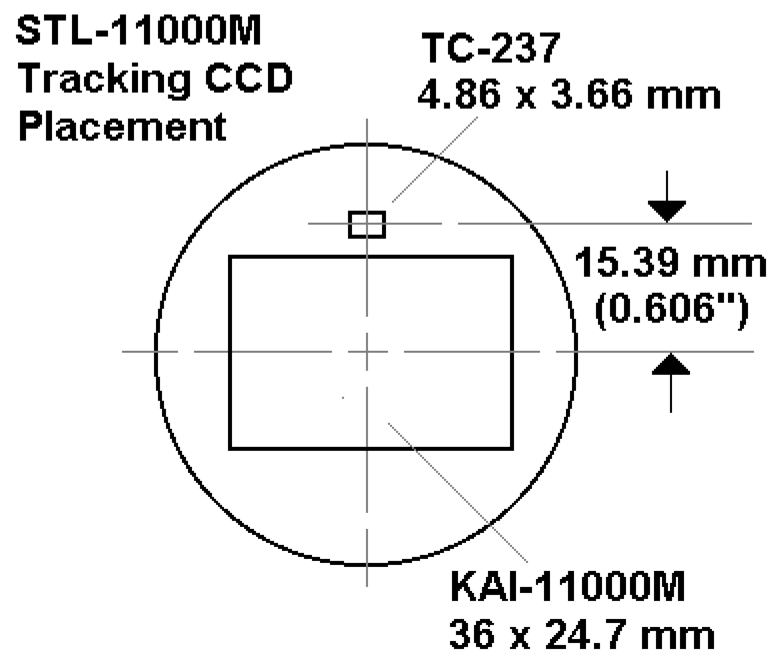

ST-9XE
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
8.69 mm
1.74 mm
KAF-0261E
10.24 x 10.24 mm


ST-10XE/XME
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
9.19 mm
2.36 mm
KAF-3200E/ME
14.85 x 10.01 mm


STL-1001E
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
16.51mm
(0.650")
KAF-1001E
24.6 X 24.6 mm


STL-1301E
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
12.56 mm
(0.49")
KAF-1301E
20.5 X 16.4 mm

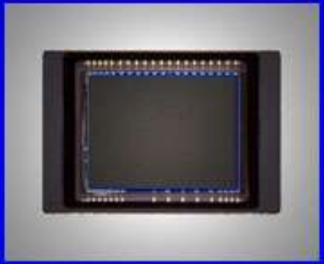

STL-6303E
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
14.4 mm
(0.568")
KAF-6303E
27.5 X 18.4 mm


STL-11000M
Tracking CCD
Placement
TC-237
4.86 x 3.66 mm
15.39 mm
(0.606")
KAI-11000M
36 x 24.7 mm

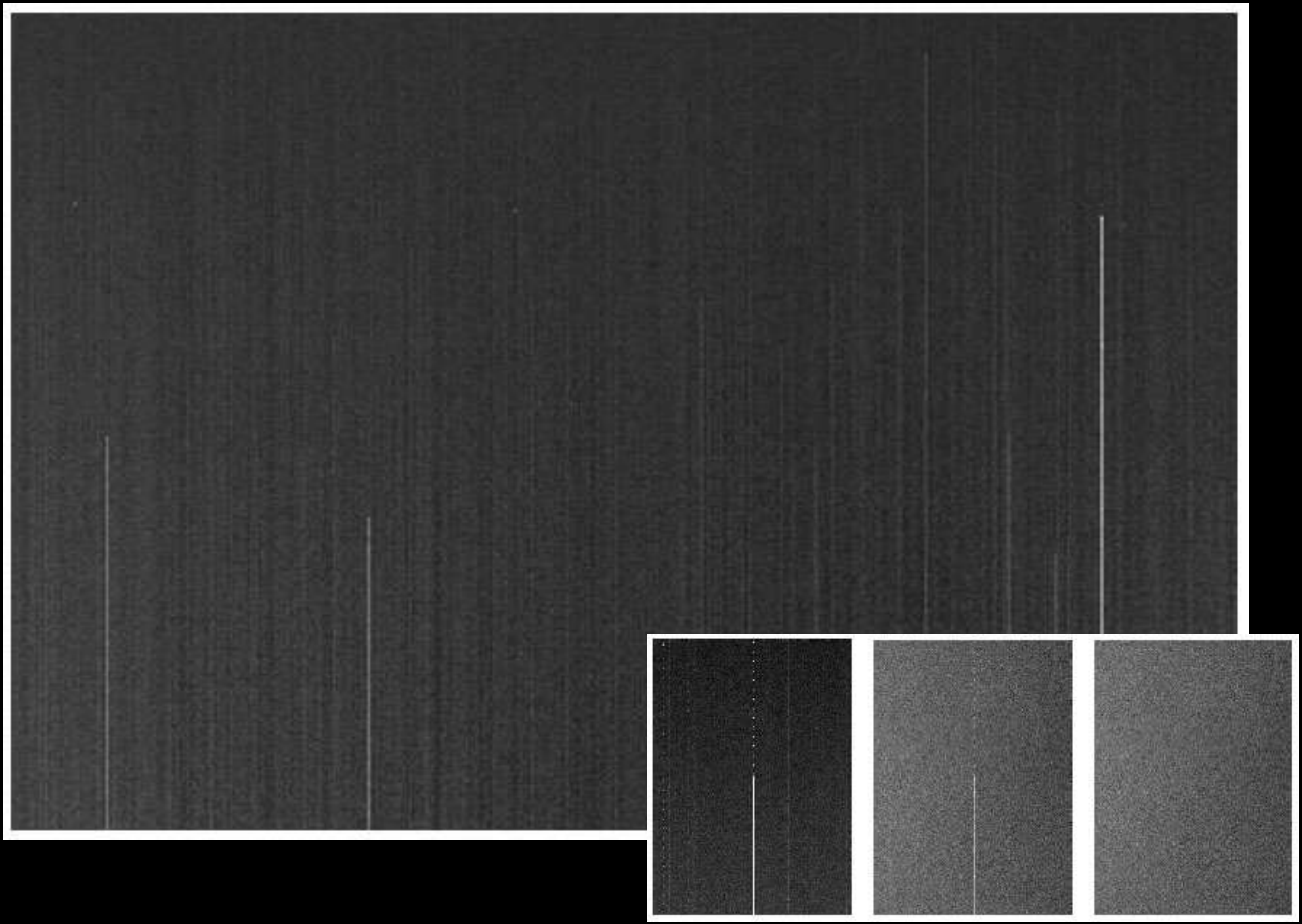
SBIG's New STX Series

STX Camera will support all the CCDs currently supported by the STL, plus

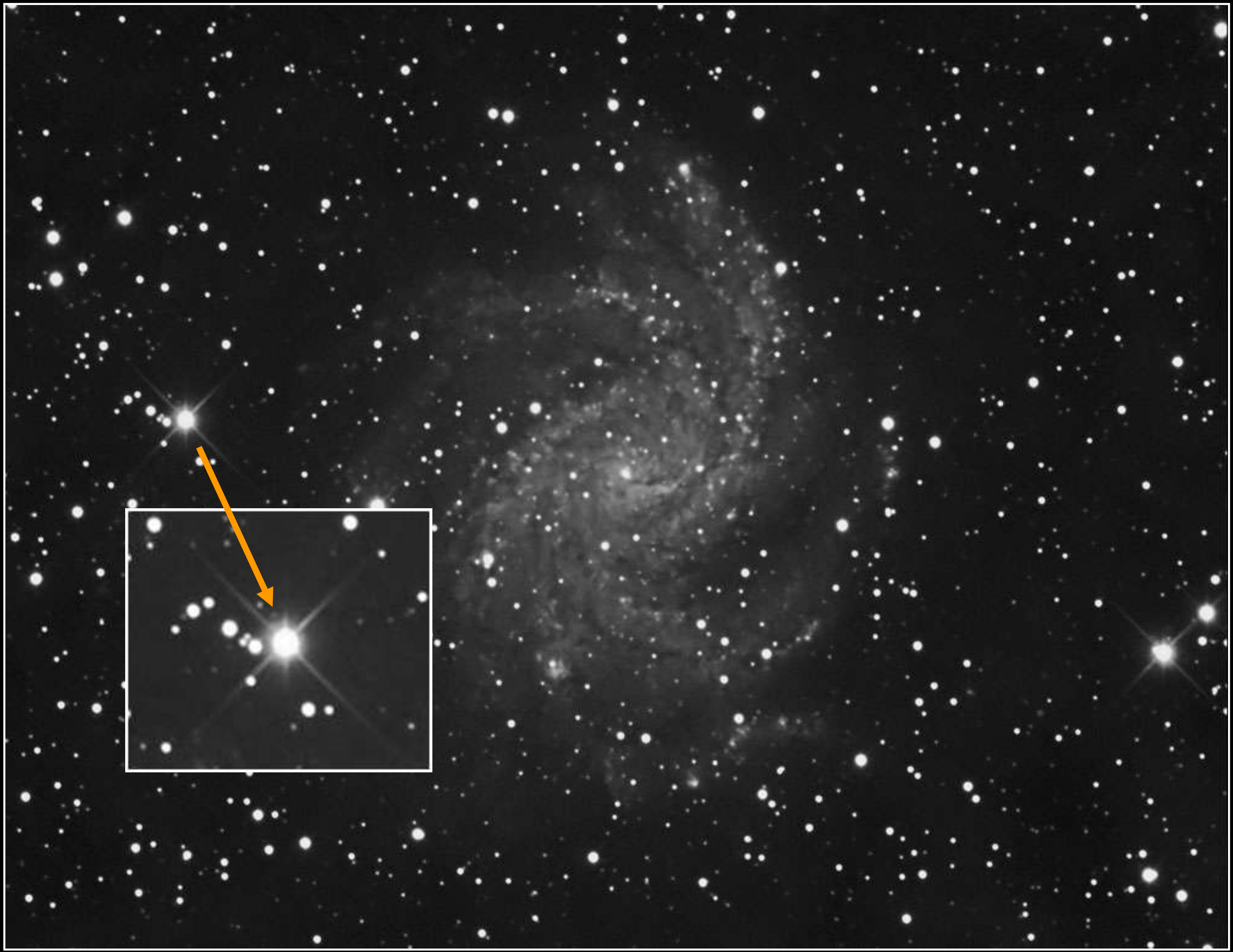
NEW CCDs	Pixels	Array	Pixel	Mono / Color	Notes
KAF-8300	8.3 Megapixels	3326 x 2504	5.4u	Mono or color	Full Frame Microlens ABG
KAI-10100	10.1 Megapixels	3648 x 2760	4.75u	Color	2x2 Color Binning
KAI-16000	16 Megapixels	4872 x 3248	7.4u	Mono or color	35mm format
KAF-9000	9 Megapixels	3056 x 3056	12u	Mono	Full Frame Microlens ABG
KAF-16803	16 Megapixels	4096 x 4096	9u	Mono	Full Frame Microlens ABG
CCD42-40	4 Megapixels	2048 x 2048	13.5u	Mono	Back illuminated High QE
CCD47-10	1 Megapixels	1056 x 1027	13u	Mono	Back illuminated High QE
CCD42-00	262,144 Pixels	512 x 512	24u	Mono	Back illuminated High QE

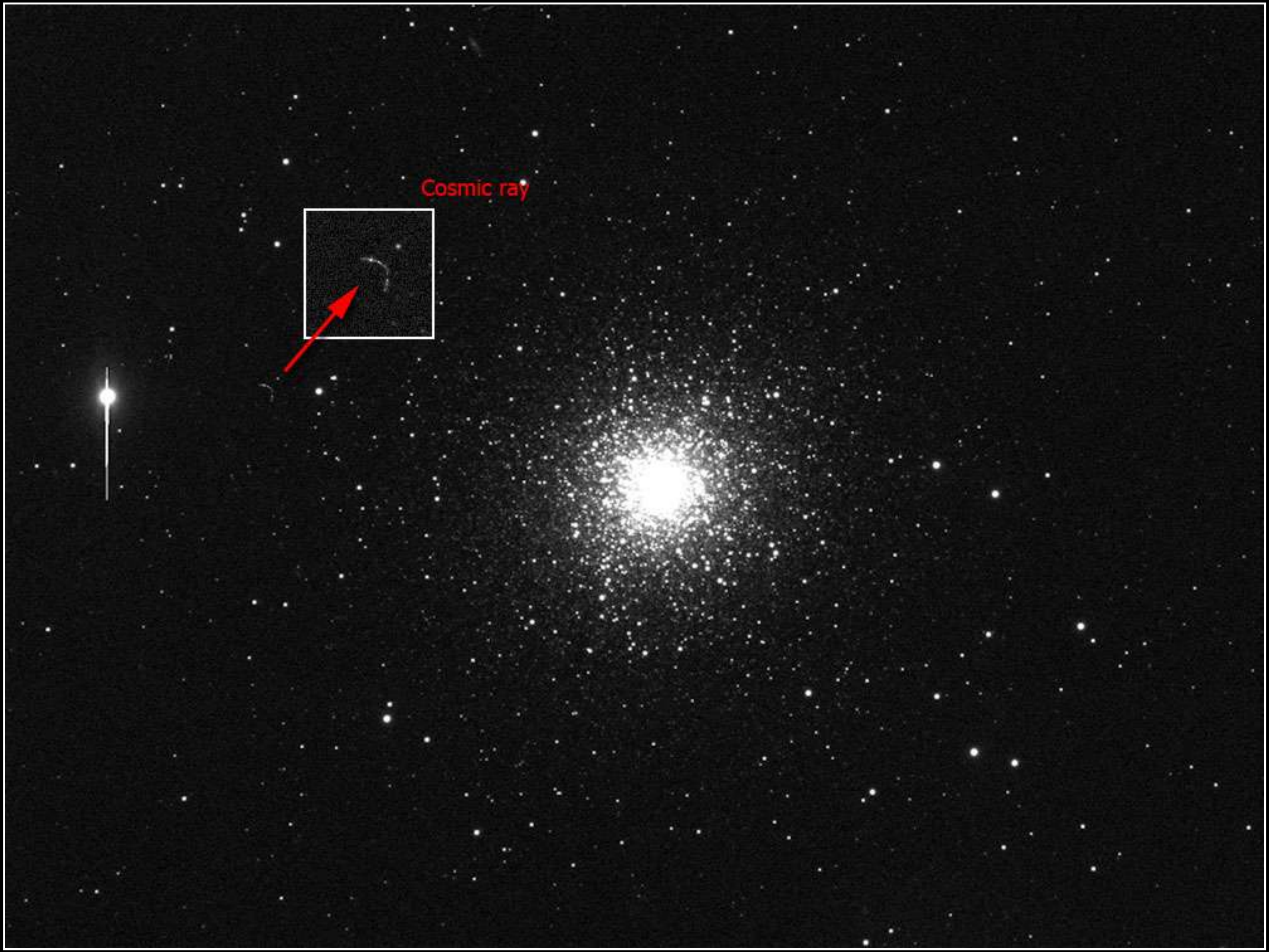
CCD Defects (Column defects)

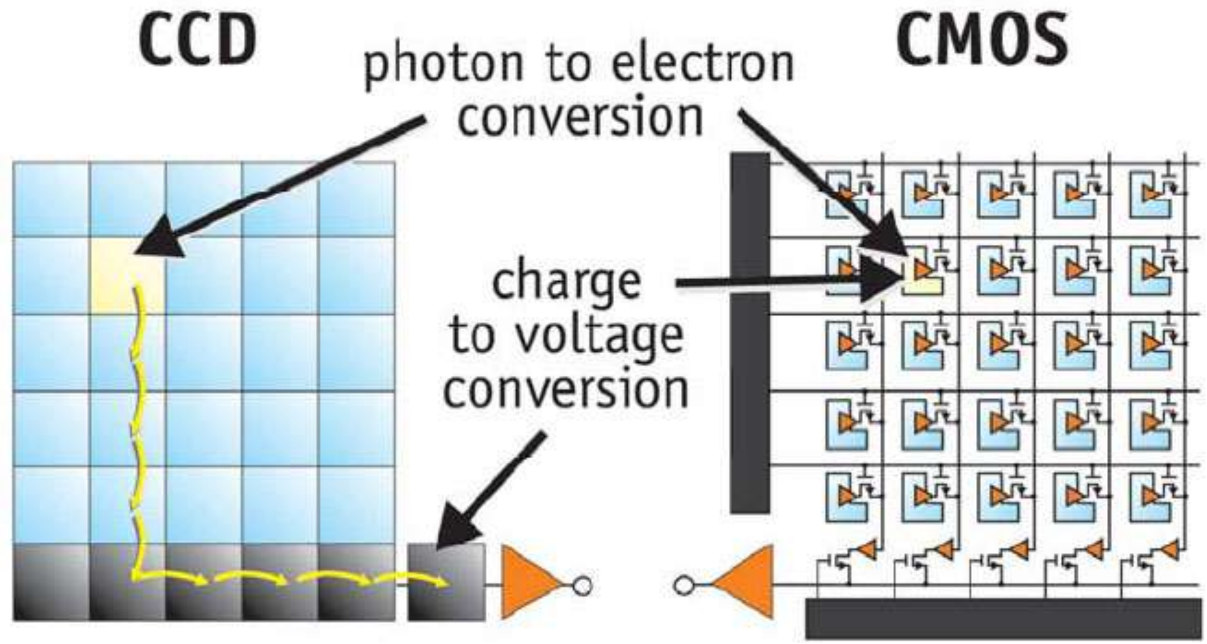


Microlens

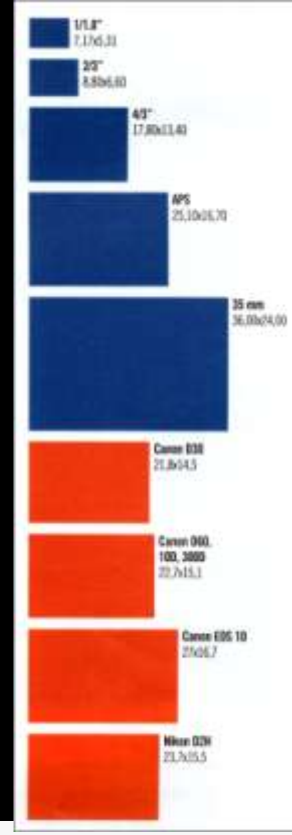


Cosmic rays

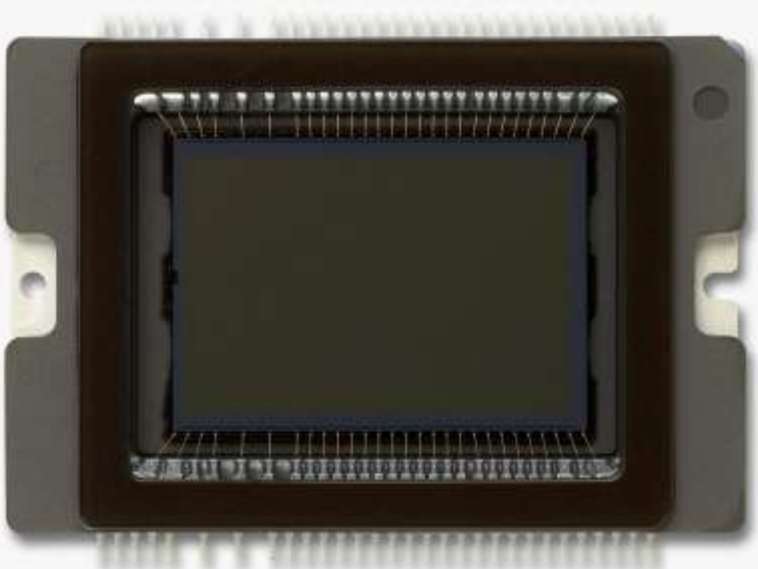




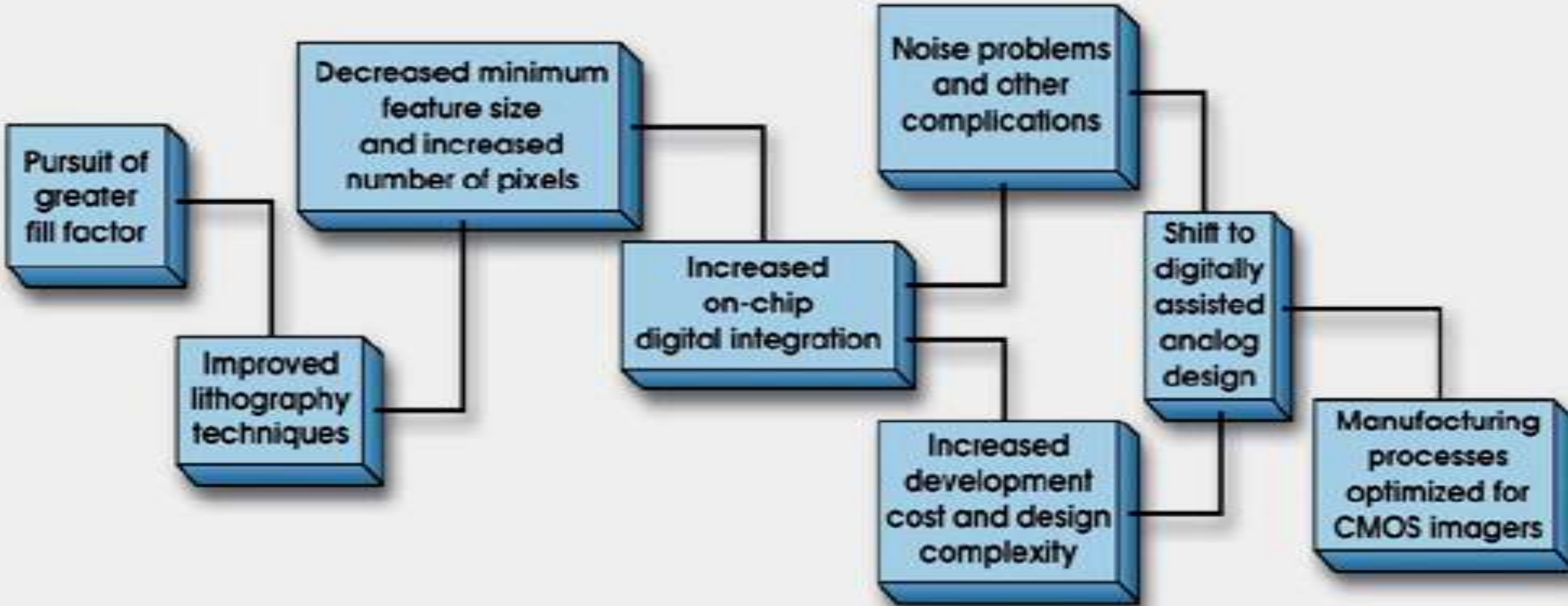
CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

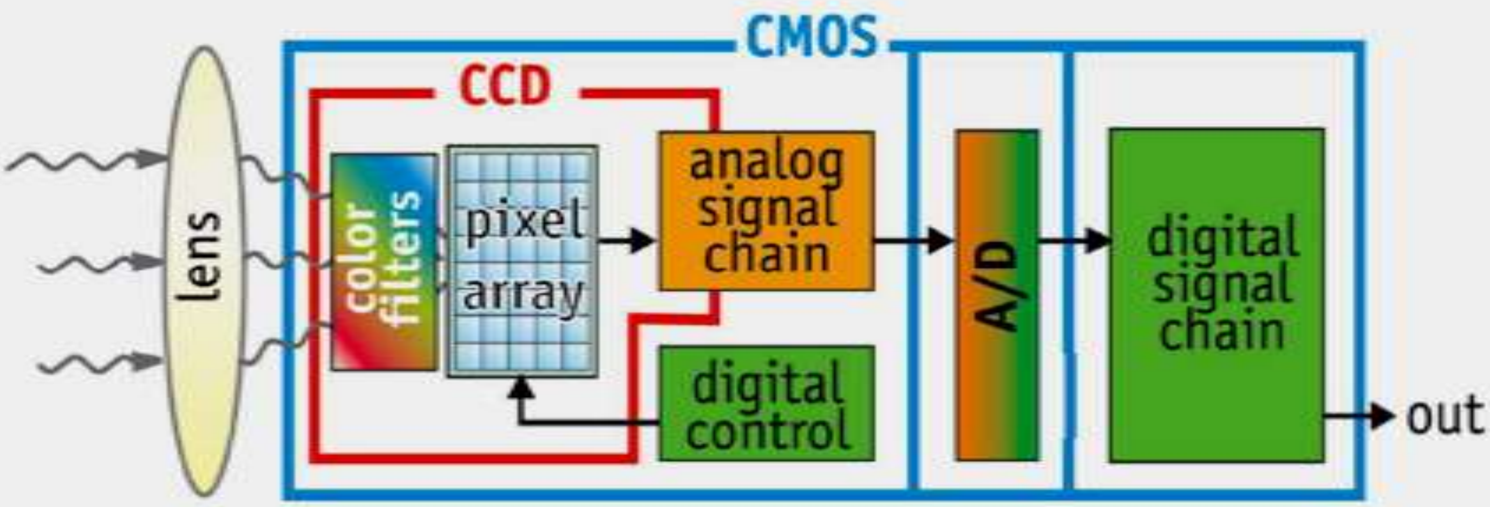


CAMERA	CCD/CMOS (mm)	DIAGONAL (mm)	RESOLUTION		PIXEL SIZE (µm)
Canon D30	21,8x14,5	26,2	2160x1440	3,11MP	10,1
Canon D60, 10D, 300D	22,7x15,1	27,3	3072x2048	6,3MP	7,4
Canon EOS 1D	27x16,7	32,3	2464x1648	4MP	10,8
Canon EOS 1Ds	24x36	43,3	4064x2704	11MP	8,85
Nikon D100	23,7x15,5	28,2	3008x2000	6,1MP	7,8
Nikon D2H	23,7x15,5	28,2	2464x1632	4MP	n/d
Pentax *istD	23,7x15,5	28,2	3008x2008	6,1MP	7,8
Olympus E-1	17,8x13,4	22,5	2560x1920	5MP	6,8



The Road to Today's CMOS Imagers





CMOS imagers can be fabricated with more "camera" functionality on the chip. This offers advantages in size and convenience.

Initial Prediction for CMOS	Twist	Outcome CMOS vs. CCD
Equivalence to CCD in imaging performance	Required much greater process adaptation and deeper submicron lithography than initially thought	High performance available in both technologies today, but with higher development cost in most CMOS than CCD technologies
On-chip circuit integration	Longer development cycles, increased cost, trade-offs with noise, flexibility during operation	Greater integration in CMOS than CCD, but companion ICs still often required with both
Reduced power consumption	Steady progress for CCDs diminished the margin of improvement for CMOS	CMOS ahead of CCDs
Reduced imaging subsystem size	Optics, companion chips and packaging are often the dominant factors in imaging subsystem size	Comparable
Economies of scale from using mainstream logic and memory foundries	Extensive process development and optimization required	Legacy logic and memory production lines are commonly used for CMOS imager production today, but with highly adapted processes akin to CCD fabrication

Number of Pixels in Popular DSLR Cameras

- Nikon D2Hs - 4.0 million
- Nikon D70 - 6.0 million
- Pentax *ist DS2 - 6.1 million
- Fuji S3 Pro - 6.1 million
- Canon 300D - 6.3 million
- Canon 350D - 8.0 million
- Olympus E-500 - 8.0 million
- Canon 20Da - 8.2 million
- Nikon D2X - 12.2 million
- Canon 1Ds Mark II - 16.6 million

It is generally accepted today that images from a good 8 megapixel digital camera are just about equivalent to images from the best 35mm films.

Canon (CMOS)

300D 6.34 Mp
resolution
3072x2048
Sensor
22.7x15.1mm
CMOS

350D 8.20 MP
resolution
3456x2304
Sensor
22.2x14.8mm
CMOS

20D 8.50 MP
resolution
3504x2336
Sensor
22.5x15mm
CMOS

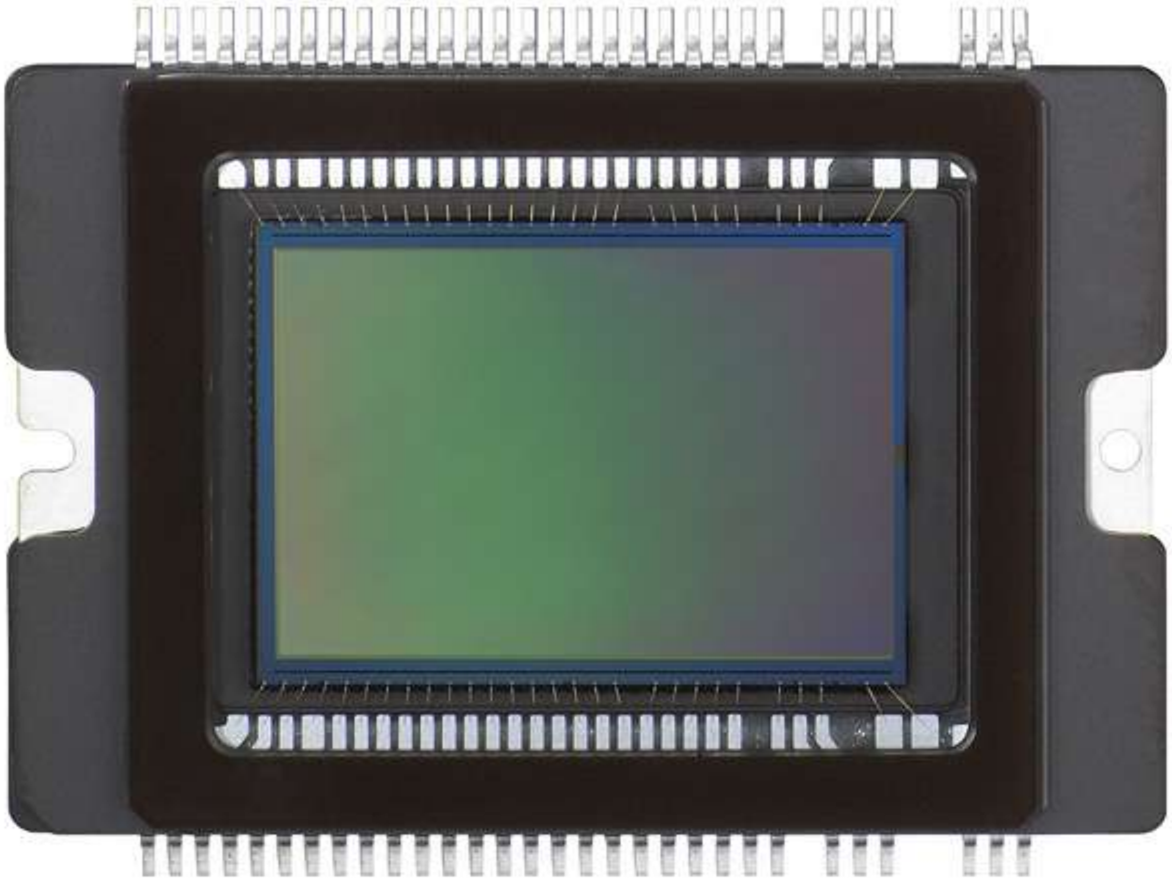
Canon (CMOS)

Recent models

EOS 20Da 8.2Mp 3504x2336 Sensor 22.5x15mm CMOS

EOS 400D 10,10 Mp 3888x2592 Sensor 22.2x14.8mm CMOS


Canon
EOS
CANON ZOOM LENS EF-S 18-55mm 1:3.5-5.6 IS
CANON LENS MADE IN JAPAN
φ58mm
450D
400D DIGITAL
MENU
DISP.
30"
F5.6
ISO 200
Av
AWB
ONE SHOT
859
SET
AF
WB
F5.0 ISO 100
JUMP
341
ISO

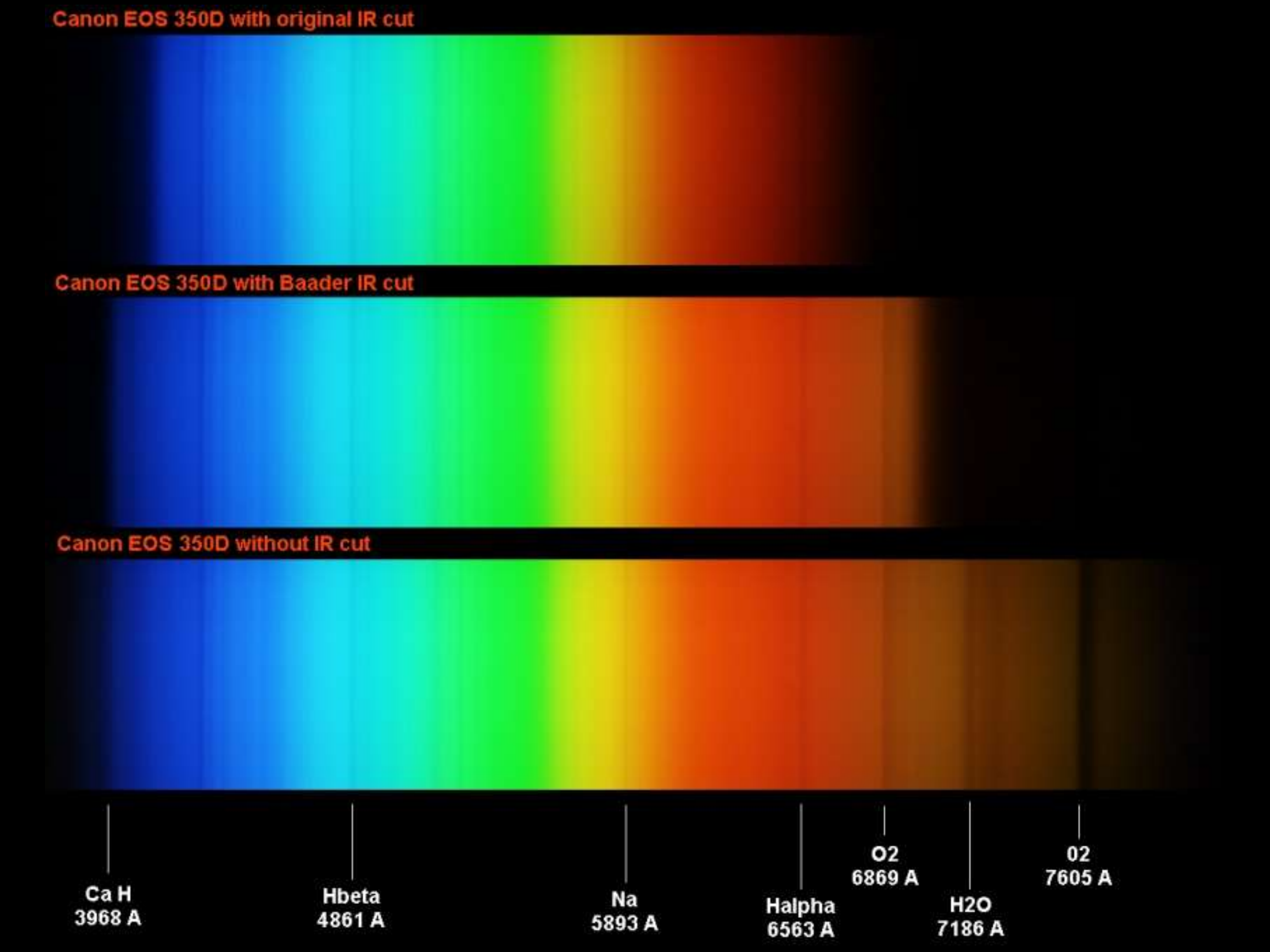


Canon 450D, 12.2 Megapixel CMOS sensor
22.2 x 14.8 mm

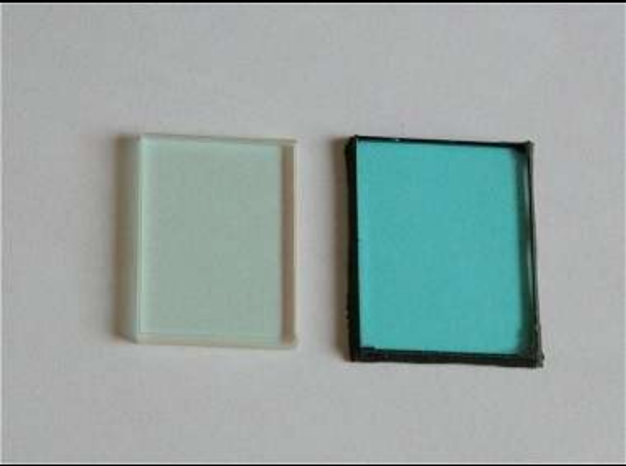
NIKON (CCD)

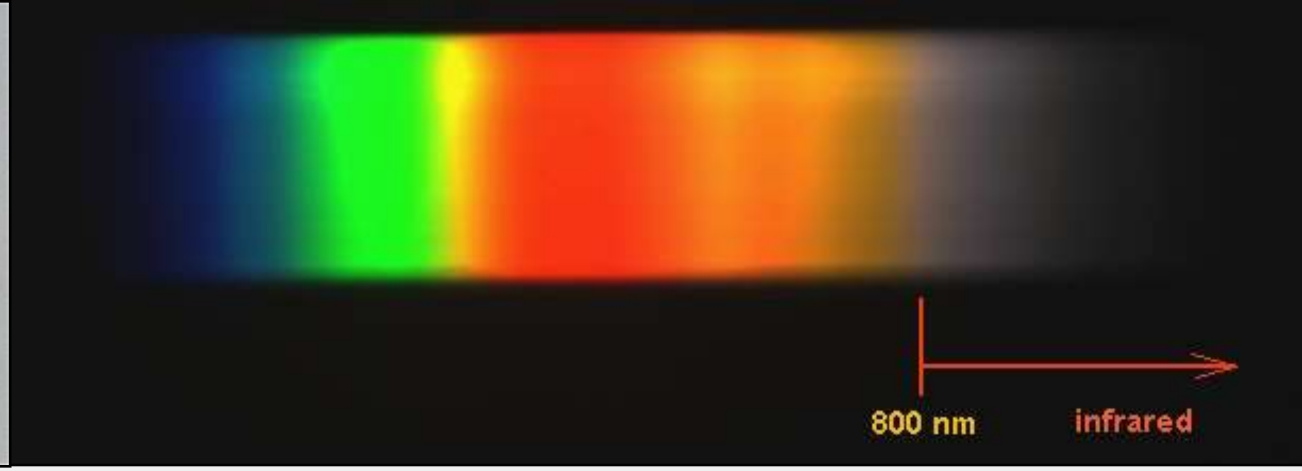

Nikon 50D 6.10 Mp
3008x2000
Sensor 23.7x15.6mm
CCD

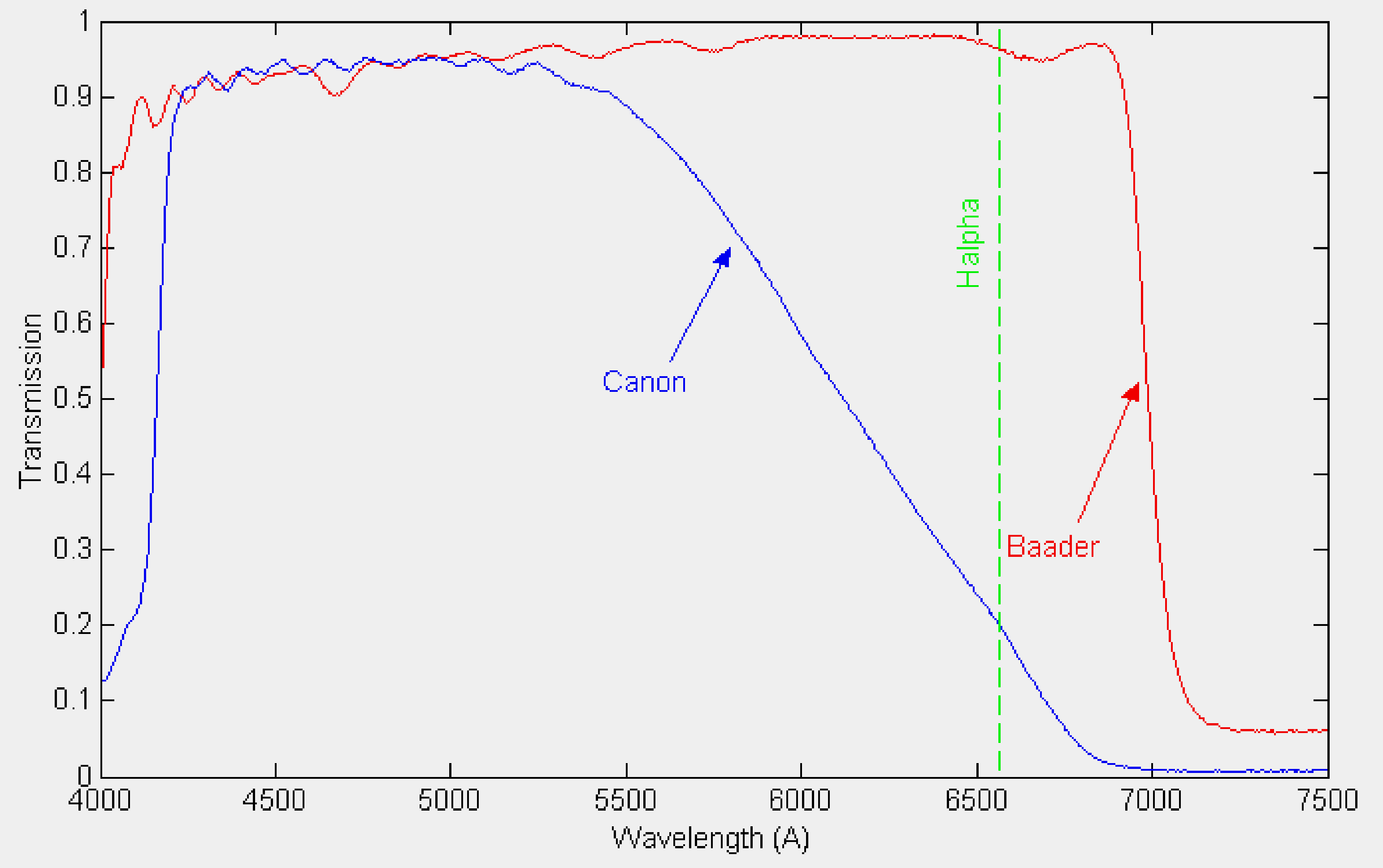

Nikon 70D 6.10 Mp
3008x2000
Sensor 23.7x15.6mm
CCD


Canon EOS 350D with original IR cut
Canon EOS 350D with Baader IR cut
Canon EOS 350D without IR cut
Ca H
3968 A
Hbeta
4861 A
Na
5893 A
Halpha
6563 A
O2
6869 A
H2O
7186 A
02
7605 A

UV/IR blocker for *Astronomical Applications*







Modified Toucam Pro (Universal WebCam adaptor)

Atik 2HS

Lumenera corporation

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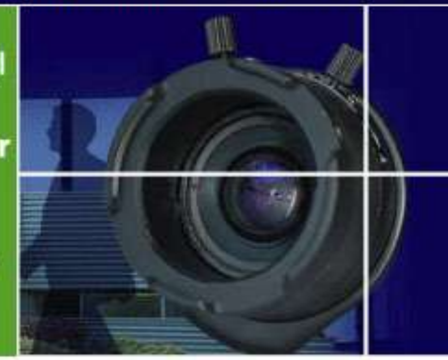
Lumenera wins OCRI **Technology Company of the Year** and OBJ's **Ottawa's Fastest Growing Company** Awards!



Lumenera Corporation is a leading developer and manufacturer of digital cameras for industrial, scientific and security markets. Located in Ottawa, Canada, Lumenera provides an extensive range of high-performance digital cameras with unique combinations of speed, resolution and sensitivity to satisfy the demands of today's imaging applications. Lumenera also offers custom design services to Original Equipment Manufacturer (OEM) partners requiring specialized hardware and software features. Read more about Lumenera >

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Inspection
High-Speed
Embedded OEM

Scientific

Brightfield
Fluorescent
Forensic
Documentation

Security

Surveillance
Transportation
Homeland Security
Military

Astro

CCD
Astrophotography
SKYnyx

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