CCD cameras in astronomy

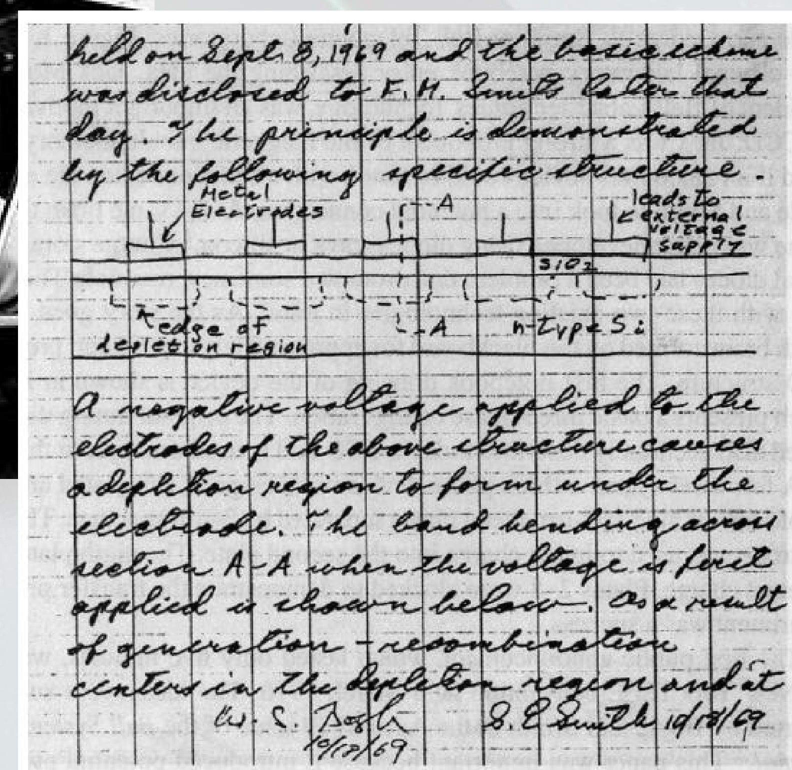
Pavel Cagas
Moravian Instruments

e-mail: pc@gxccd.com
www: http://www.gxccd.com/
http://www.tcmt.org/

The origin of CCD detectors

- Canadian physicist Willard S. Boyle and his American colleague George E. Smith (both employes of the Bell Laboratories) created the first CCD chip – a silicon circuit capable to change light into electric signal – in 1969.
- They were awarded with many prizes for this invention, the most important one is the Nobel prize for physics in 2009.
- Similarly to many important inventions, also in the case of the invention of the CCD there are disputes who was really the first coming with the idea of silicone light detector.

Willard S. Boyle and George E. Smith



held on Sept. 8, 1969 and the basic scheme was disclosed to F. M. Smits later that day. The principle is demonstrated by the following specific structure.

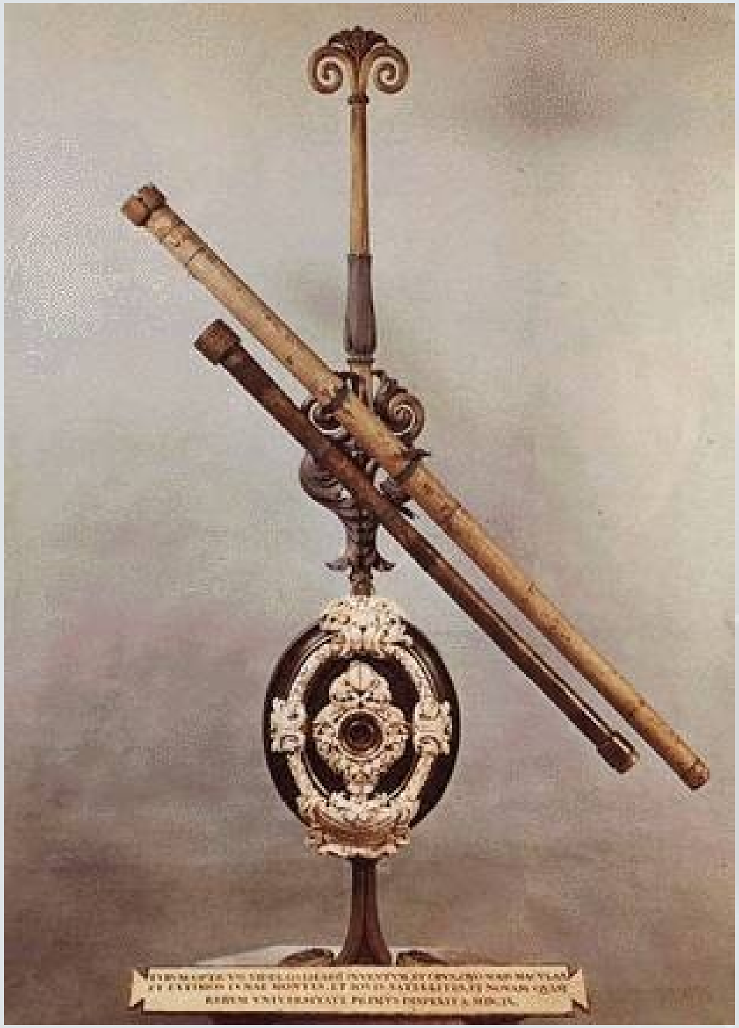
A negative voltage applied to the electrodes of the above structure causes a depletion region to form under the electrode. The band bending across section A-A when the voltage is first applied is shown below. As a result of generation - recombination centers in the depletion region and at

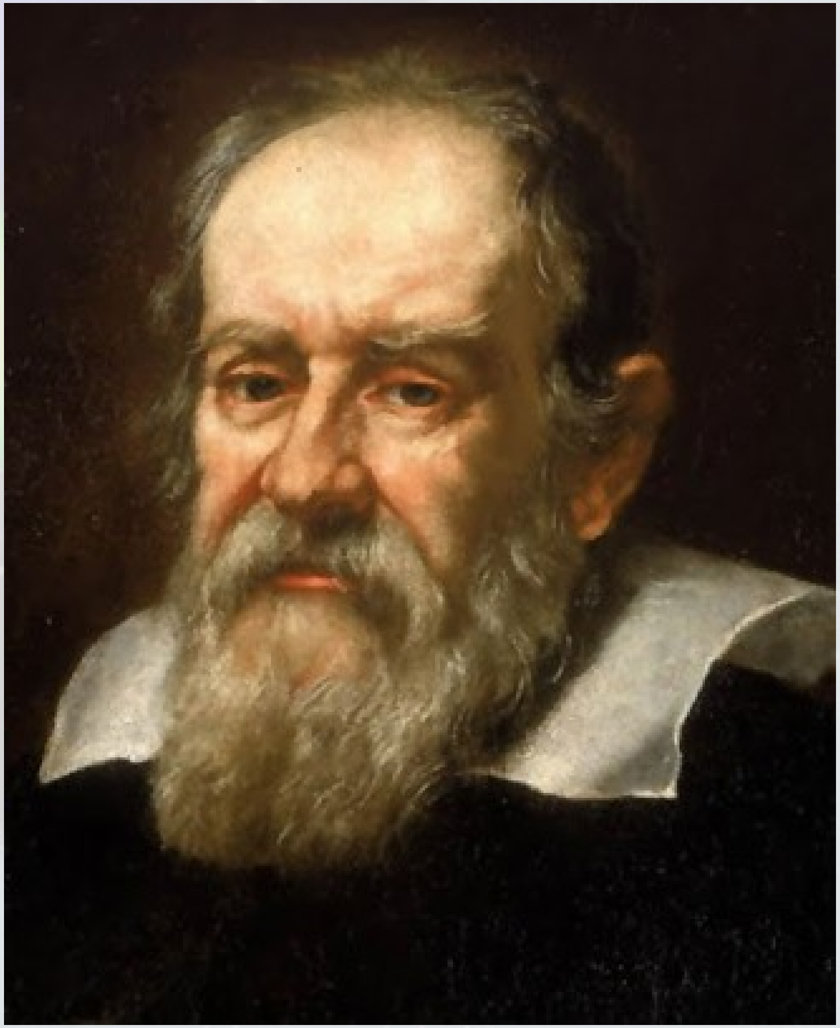
W. S. Boyle
10/18/69

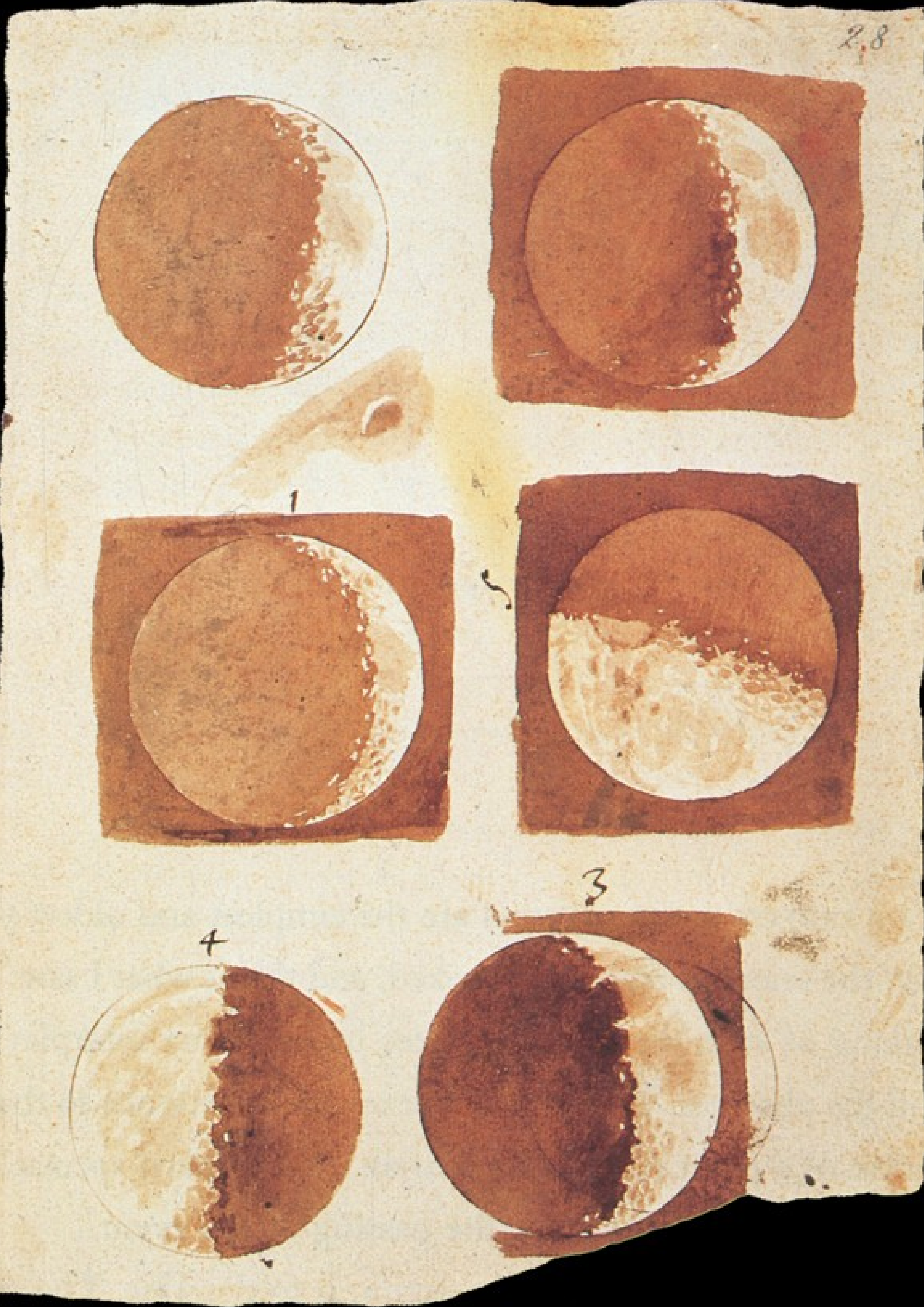
G. E. Smith 10/18/69

A brief history of instruments and detectors in observational astronomy

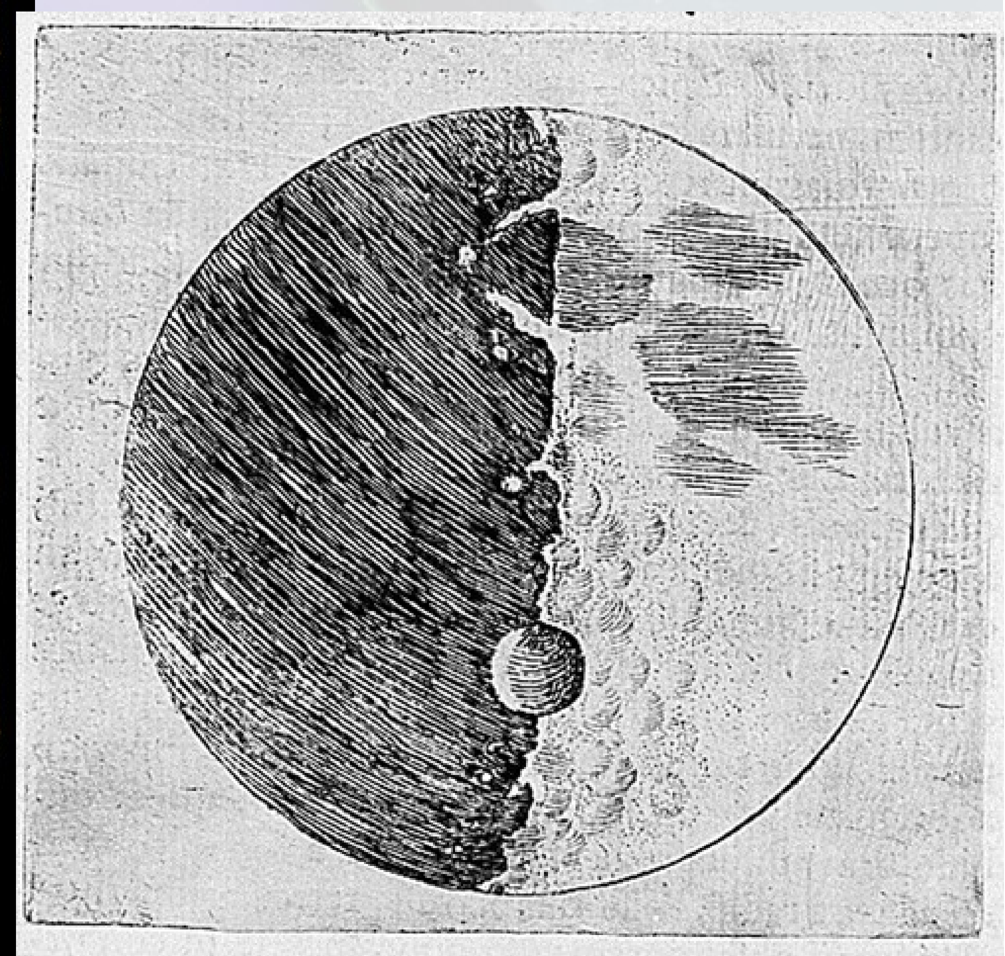
The 1st revolution in astronomy:
The telescope
(Galileo Galilei, 1609)

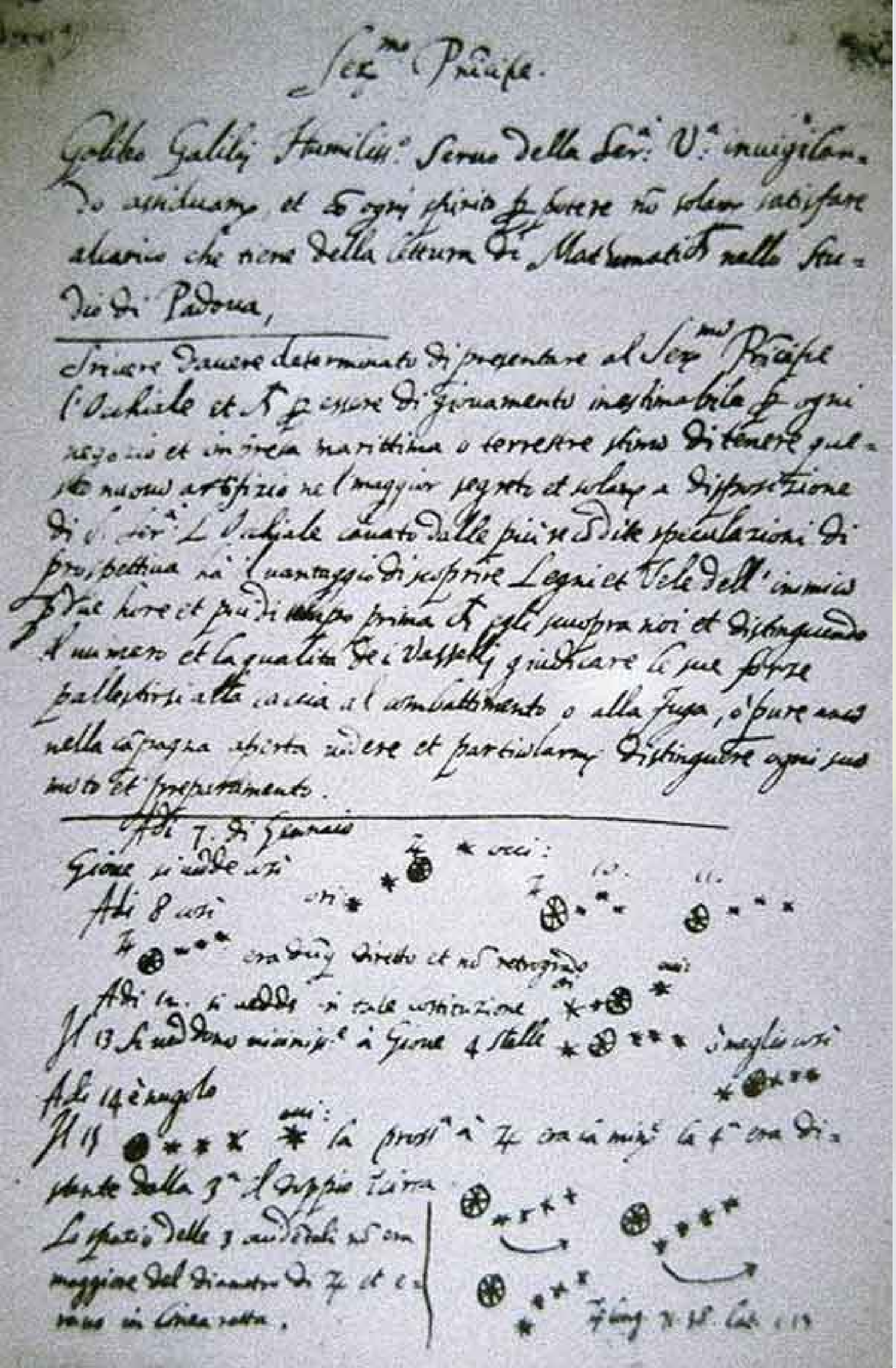






- The Moon is a world, similar to the Earth.
- There are mountains and valleys...





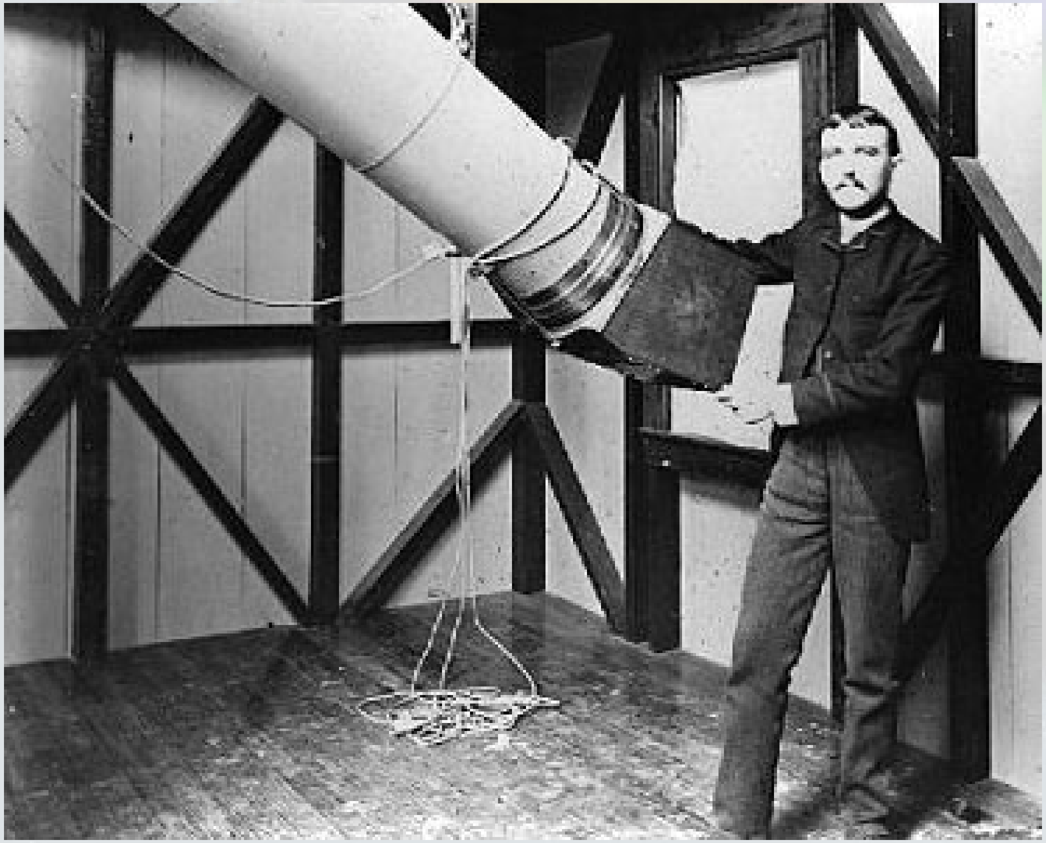
- The planets are not just points, they appear as discs.
  - Venus shows phases similar to the Moon.
- There are satellites circling the planets.
  - Galileo discovered 4 greatest satellites of Jupiter.
- The glow of the Milky is in fact the glow of many individual stars, which cannot be distinguished without a telescope.

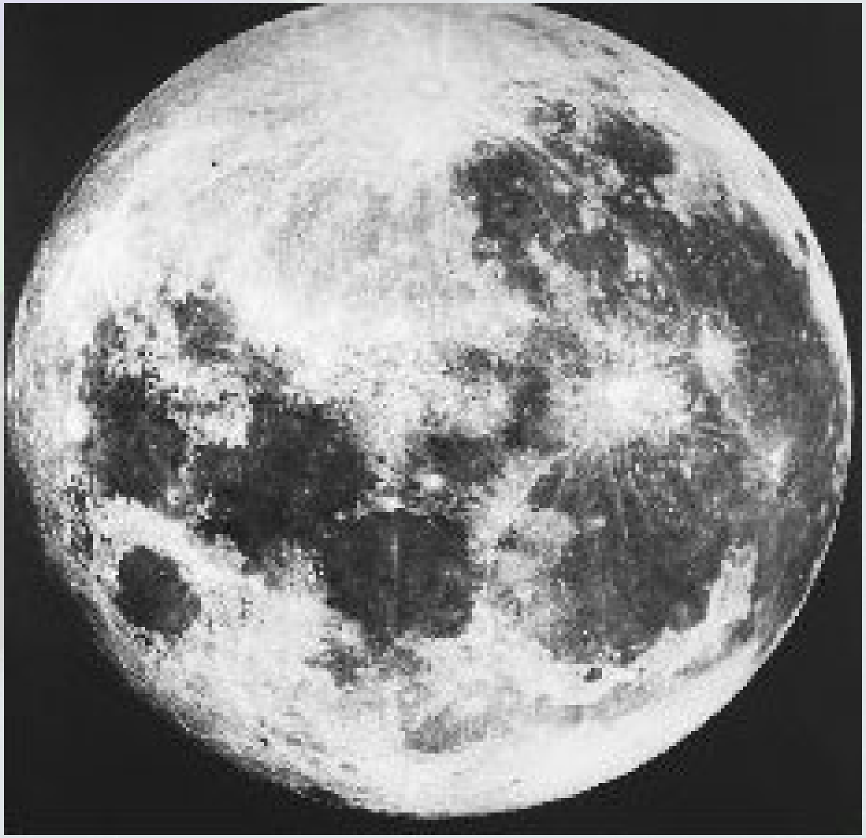
The 2nd revolution in astronomy: **The photography** (Louis Daguerre, 1839)

- Daguerre announced the invention of the process, allowing preserving of the light image in January 1839.
- A couple of months before this announcement, the first image of the Moon, acquired by Daguerre's friend and supporter François Arago, was released.
  - Apparently, the astro-photography was here before the general photography :).

Henry Draper

- The first photography of the Great Orion Nebula.
- Image of the Moon, captured in 1880.



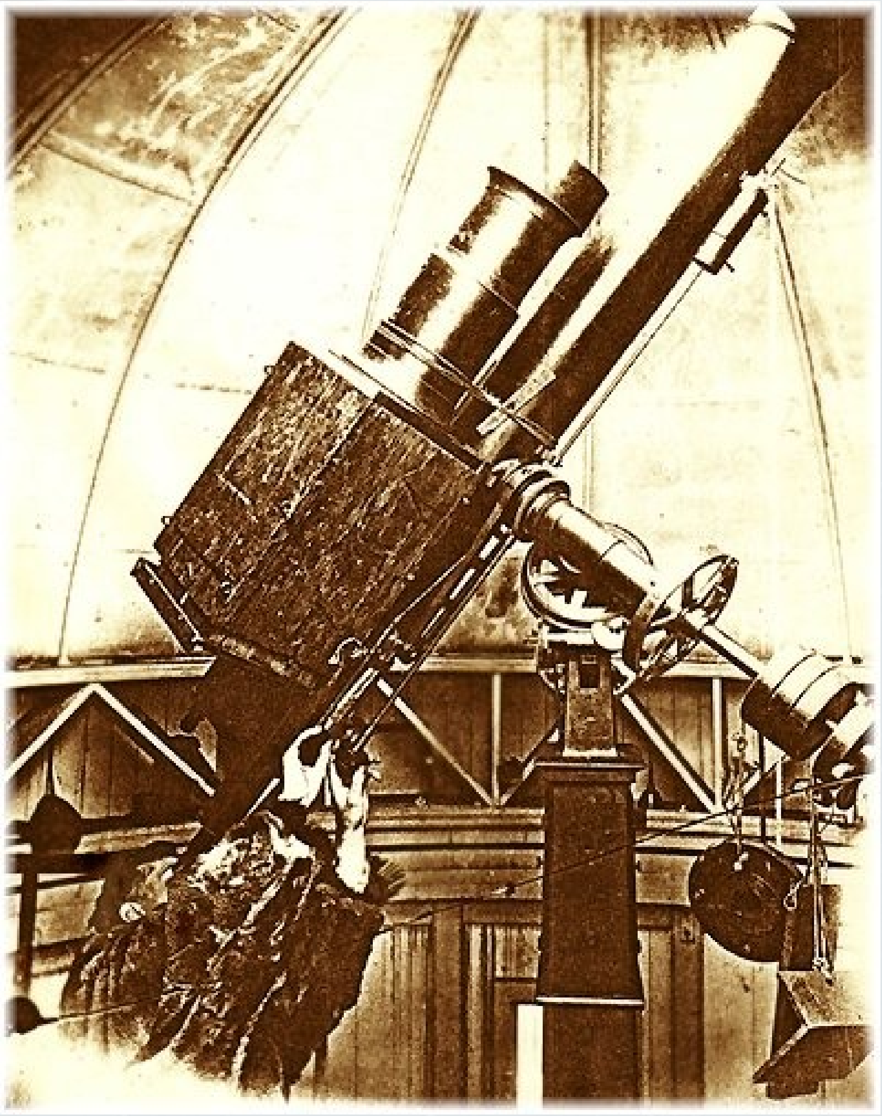


Photography can accumulate light

- In contrary to the human's eye and brain, which process the image created on retina continuously, photographic emulsion is capable of accumulating incoming light for a long time.
  - Prolonging of exposures leads to acquiring dim astronomical objects, which cannot be seen by an eye, no matter if a telescope is used.
- In addition, the photographic plate offers another possibilities of processing:
  - measuring a star position
  - measuring a star brightness

The photography shows us the real Milky Way

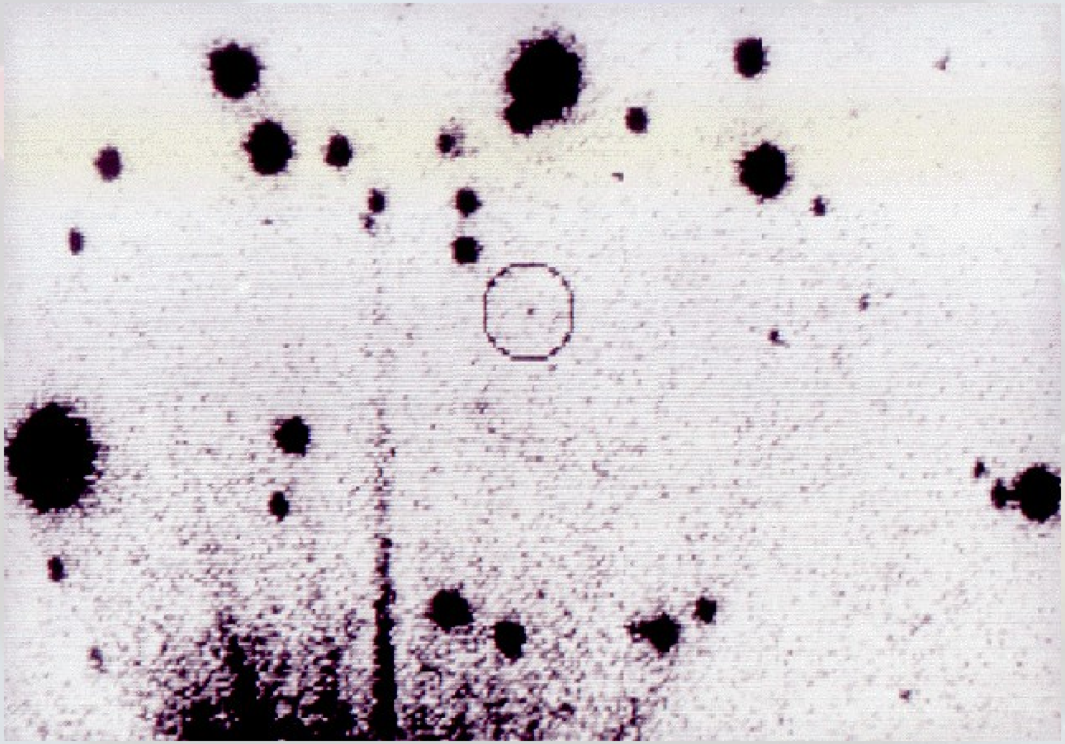
- Edward Emerson Barnard imaged the Milky Way and discovered numerous diffuse and dark nebulae.
- He discovered:
  - 19 NGC catalog objects
  - 131 IC catalog objects
- Barnard working with the Crocker Telescope at the Mt. Hamilton.



Photography on the top

- Astronomical photography is the most important method of capturing light in astronomical research during the second half of the 20th century.
- Many hours long exposures, acquired with the biggest contemporary telescope on Mt. Palomar (mirror of 5m diameter), shows remote stars and galaxies up to 23rd mag.
- The complete sky was photographed in red and blue colors using a wide-field Schmidt photographic telescope with 1.2m diameter on the same observatory.

The 3rd astronomical revolution: **CCD and digital image processing** (Willard S. Boyle, George E. Smith)

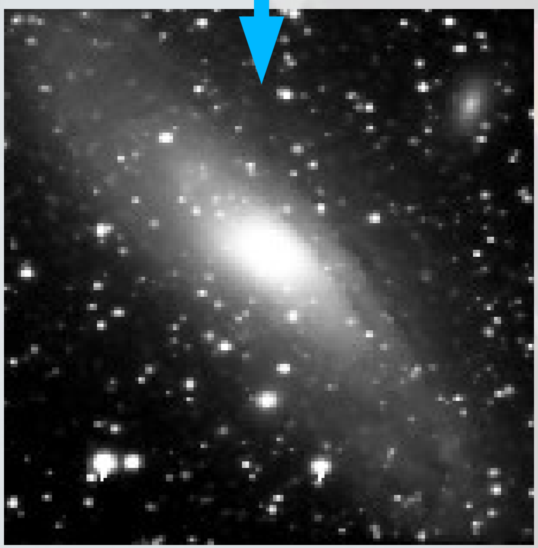


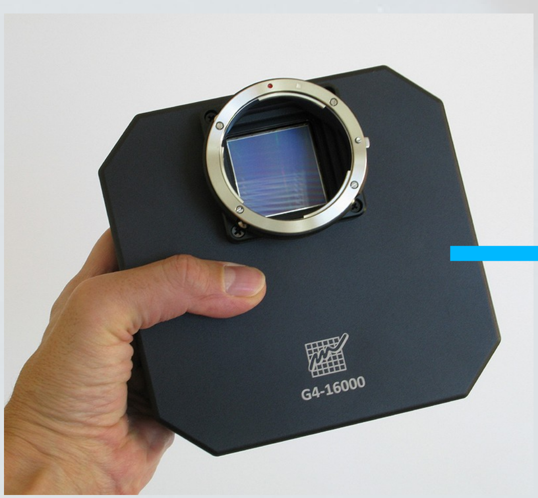
- The 200inch (5m) telescope on the Mt. Palomar mountain used the CCD camera to discover the core of the Halley comet 1.6 billion km from Earth on the October 16th, 1982.

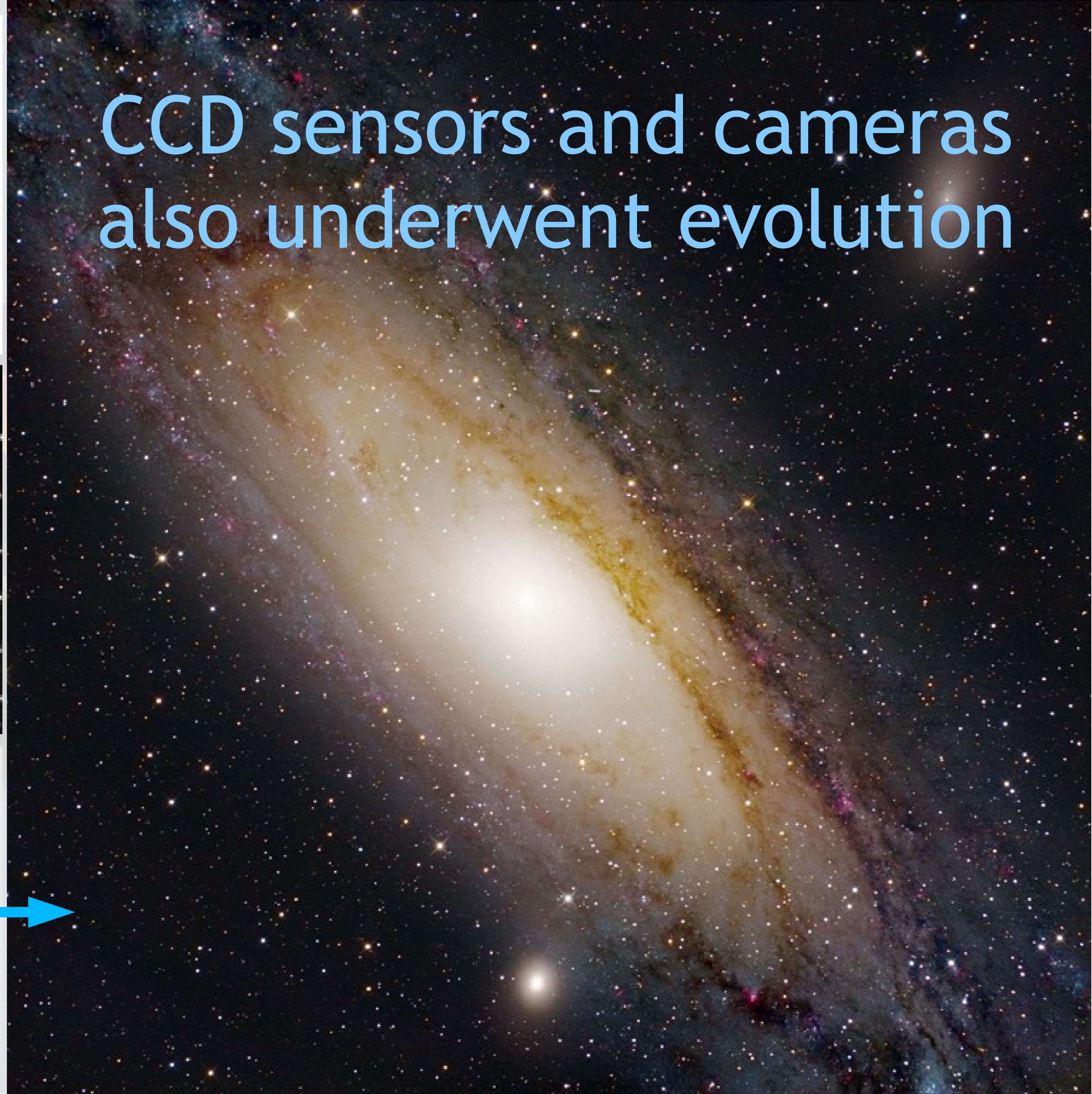
Charge Coupled Device

- CCD was originally used in the TV cameras as a replacement for vidicon (vacuum-tube based light sensors). Thanks to much less weight, dimensions and power consumption, CCD chips allowed to build significantly smaller and lighter cameras with a higher sensitivity.
- The first space probe, equipped with the CCD detectors instead of vidicon tubes, was Galileo spacecraft. Galileo camera resolution was only 800×800 pixels.
  - Galileo predecessors, including the famous Mariner and Voyager probes, used classical TV cameras with vacuum tubes or even the very simple scanning photometers (e.g. the Pioneer probes)

CCD sensors and cameras also underwent evolution







A telescope with a CCD camera compares to a 10-times greater telescope with a film

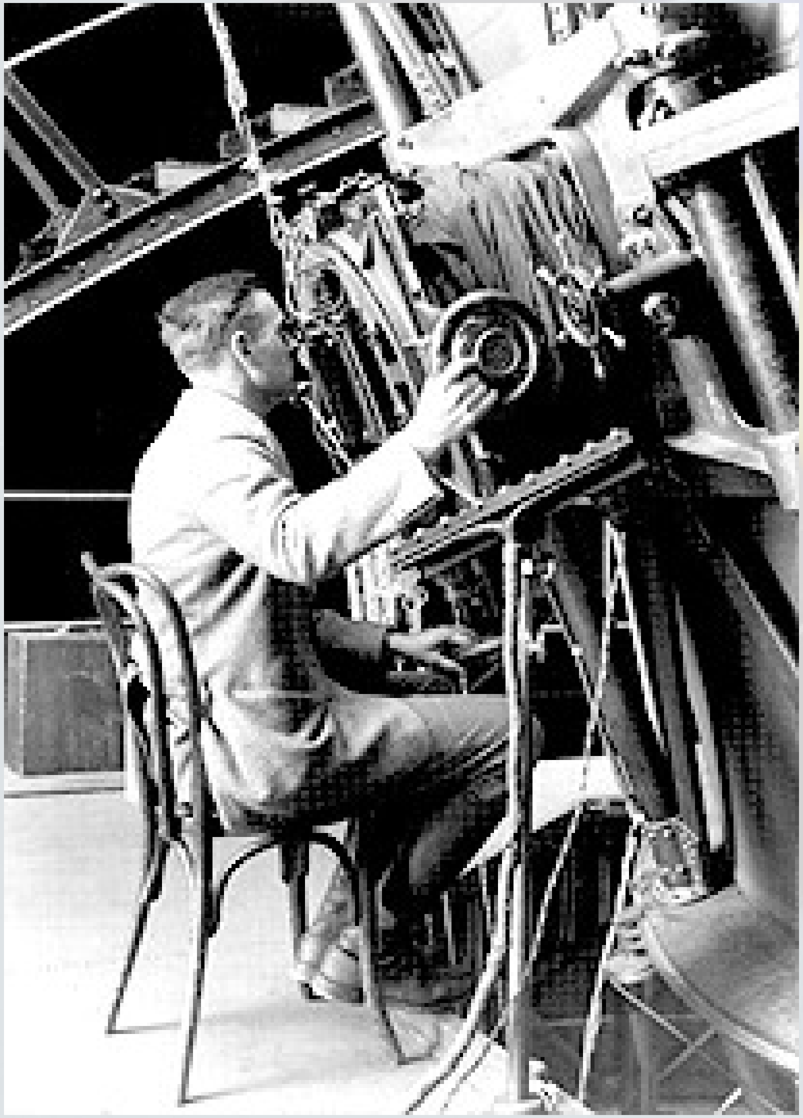
- Let's compare a few images from a famous book of J. Grygar, Z. Horsky and P. Mayer “The Universe”.
- Images on the left side are captured on the world-class observatories (mainly on the U.S. Naval Observatory) before the CCD era.
- Images on the right side are captured by amateurs with 25 cm off-the-shelf telescope from backyards, but with CCD cameras.

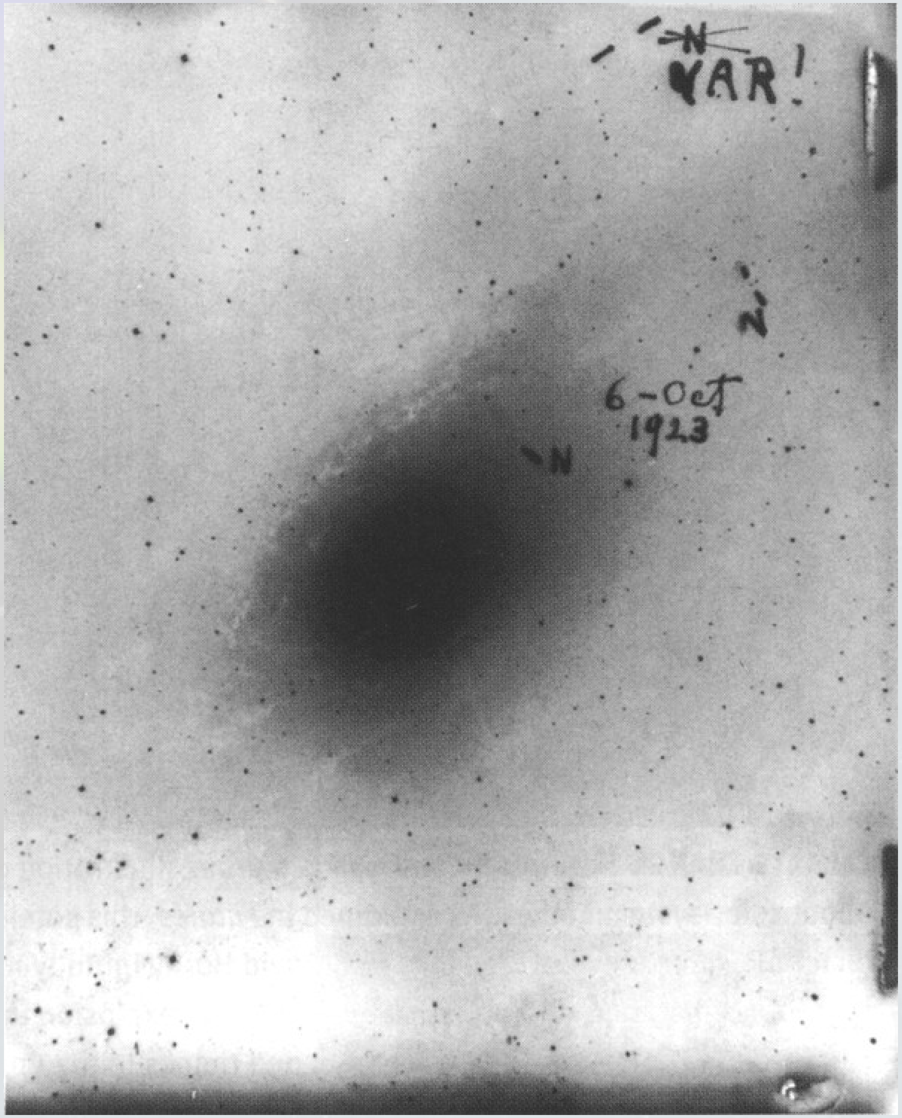
NGC 6946 “ Fireworks Galaxy”

M 51 “Whirlpool” galaxy

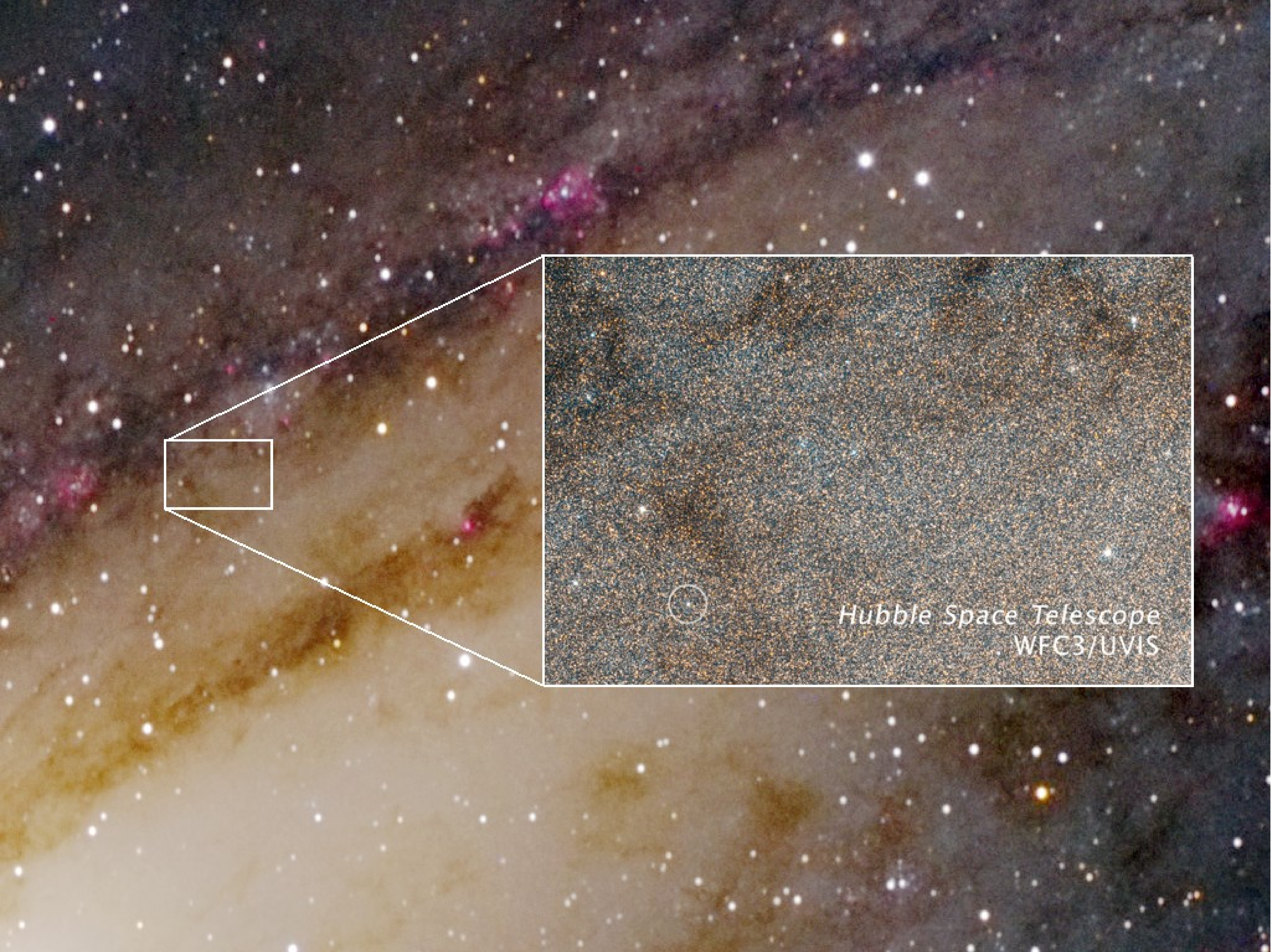
M 42 “Great Orion Nebula”

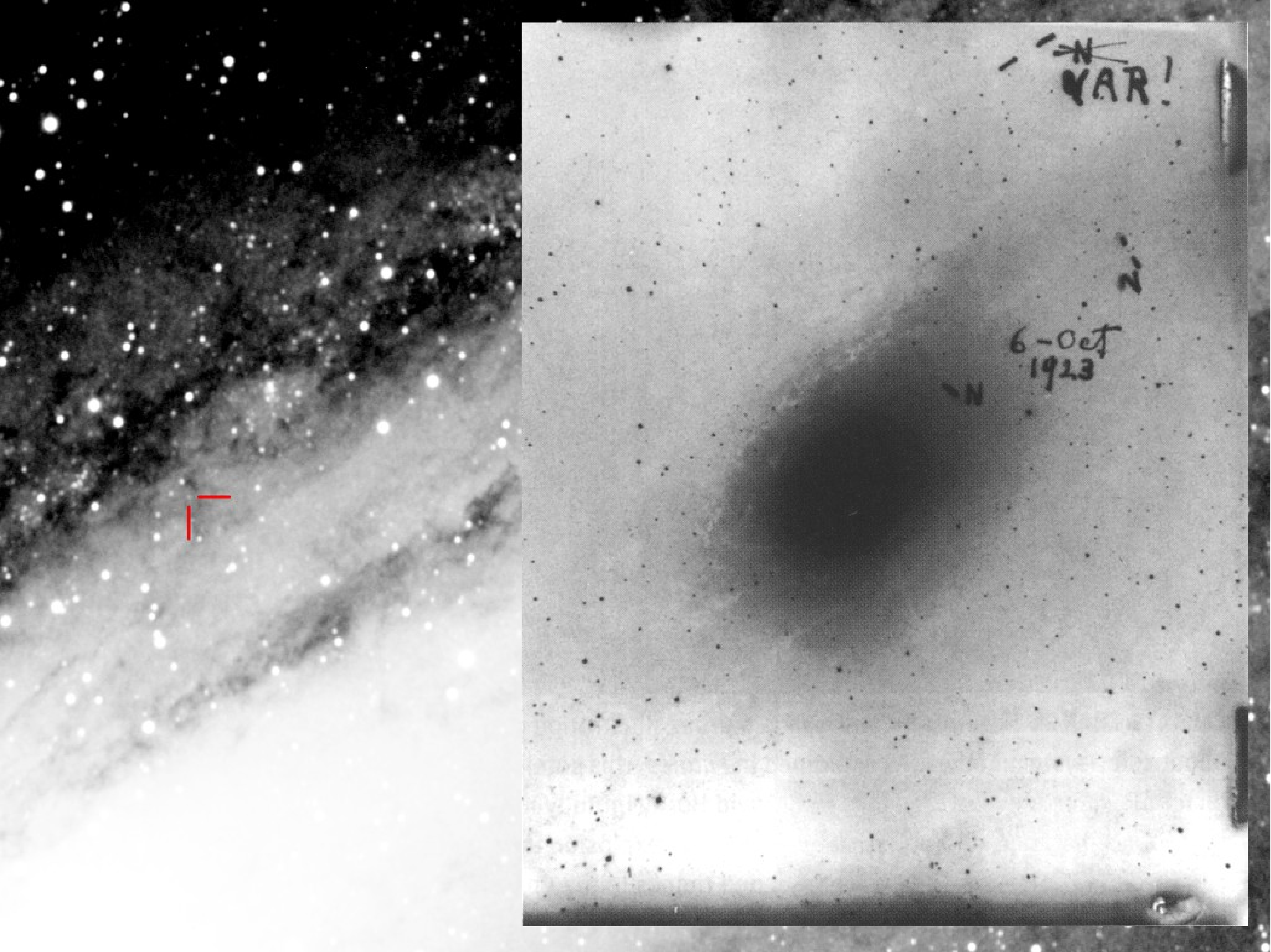
Edwin Hubble discovers Cepheid variable in M31 using 2.5 m Hooker telescope on the Mt. Wilson






Hubble Space Telescope
WFC3/UVIS


Hubble Space Telescope
WFC3/UVIS


N
VAR!
N
N
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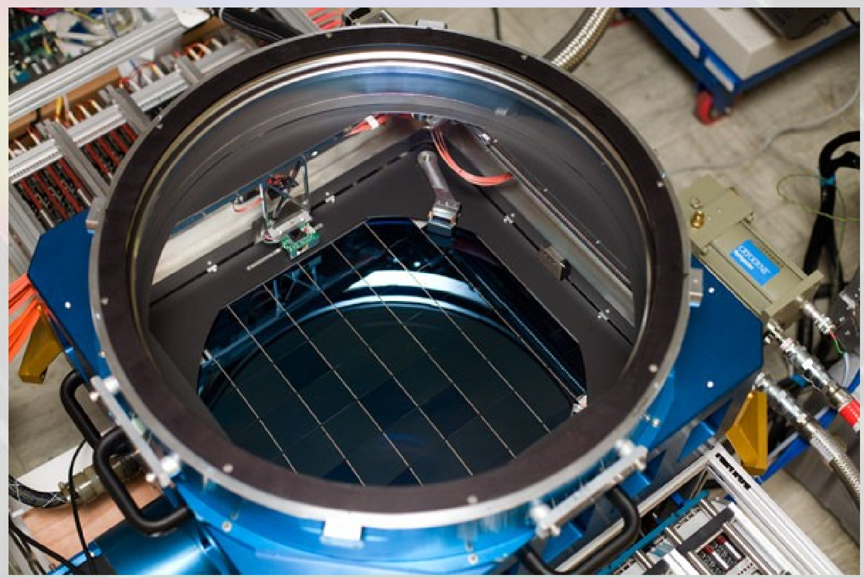
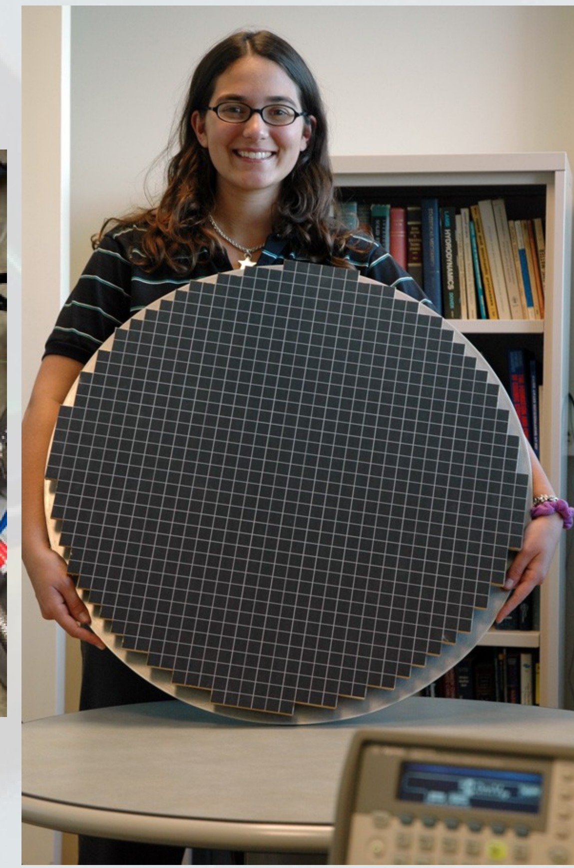
1923
N

Modern CCD detector arrays provide a giga-pixel resolution





The principles of CCD operation

How a CCD works

- Incoming light excites electrons in the semiconductor.
- Electrons cannot move freely within the silicone chip because of vertical negative potential walls, that are created during the manufacturing process.
- A grid of horizontal electrodes, also with a negative potential provided by camera electronics, creates a matrix of the “potential wells” on the chip, from which electrons cannot escape.

How a CCD works (2)

- Every potential well represents one image point – a “pixel” (an abbreviation from “picture element”).
  - Pixels exposed to more intensive light accumulate more electrons and vice versa.
- So the most important feature of the CCD detector, compared to human's eye, is the ability to accumulate charge for a long period.
  - CCDs are then able to acquire enough light even from the very dim light sources.

Charge Coupled Device

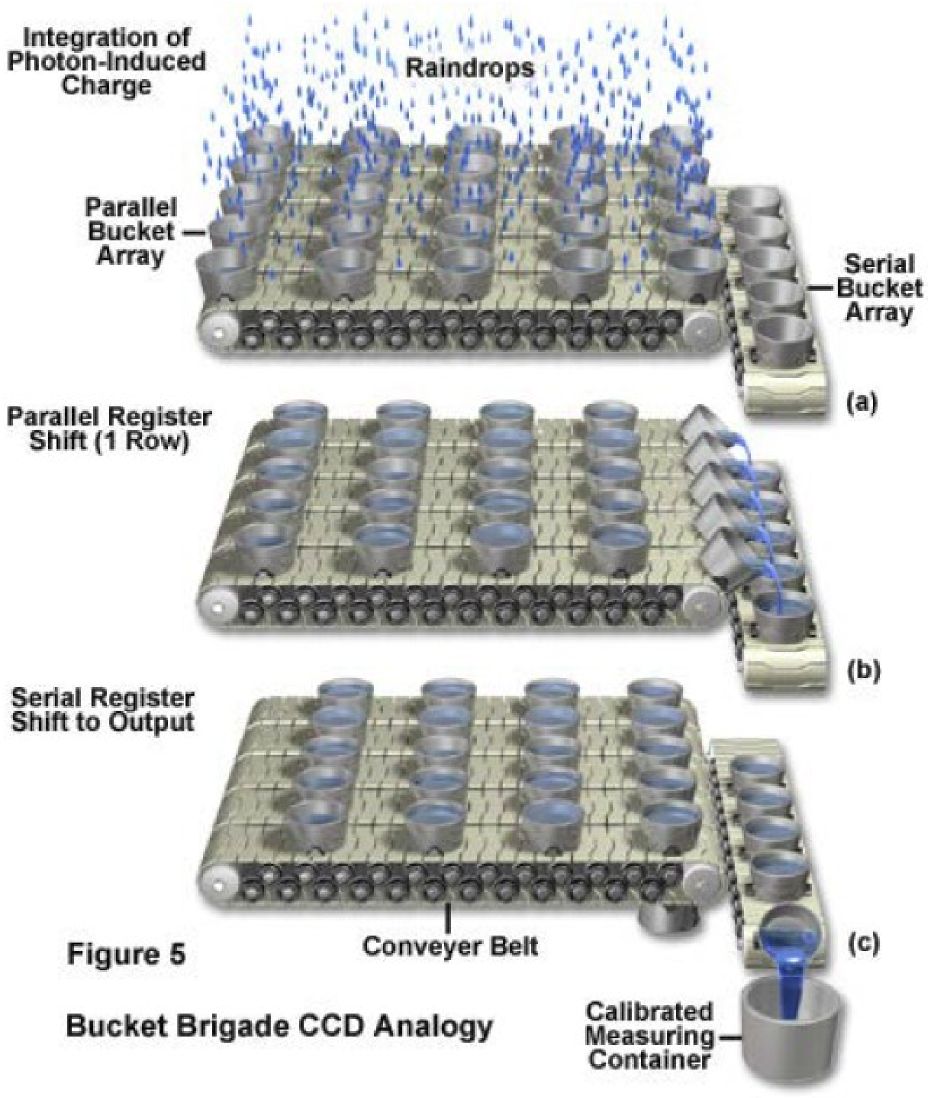
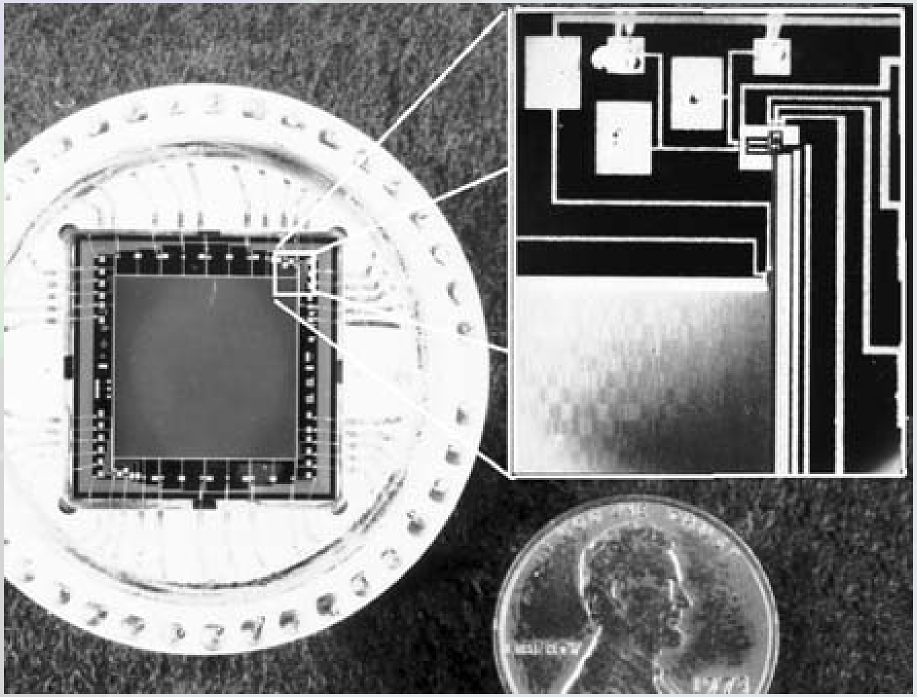
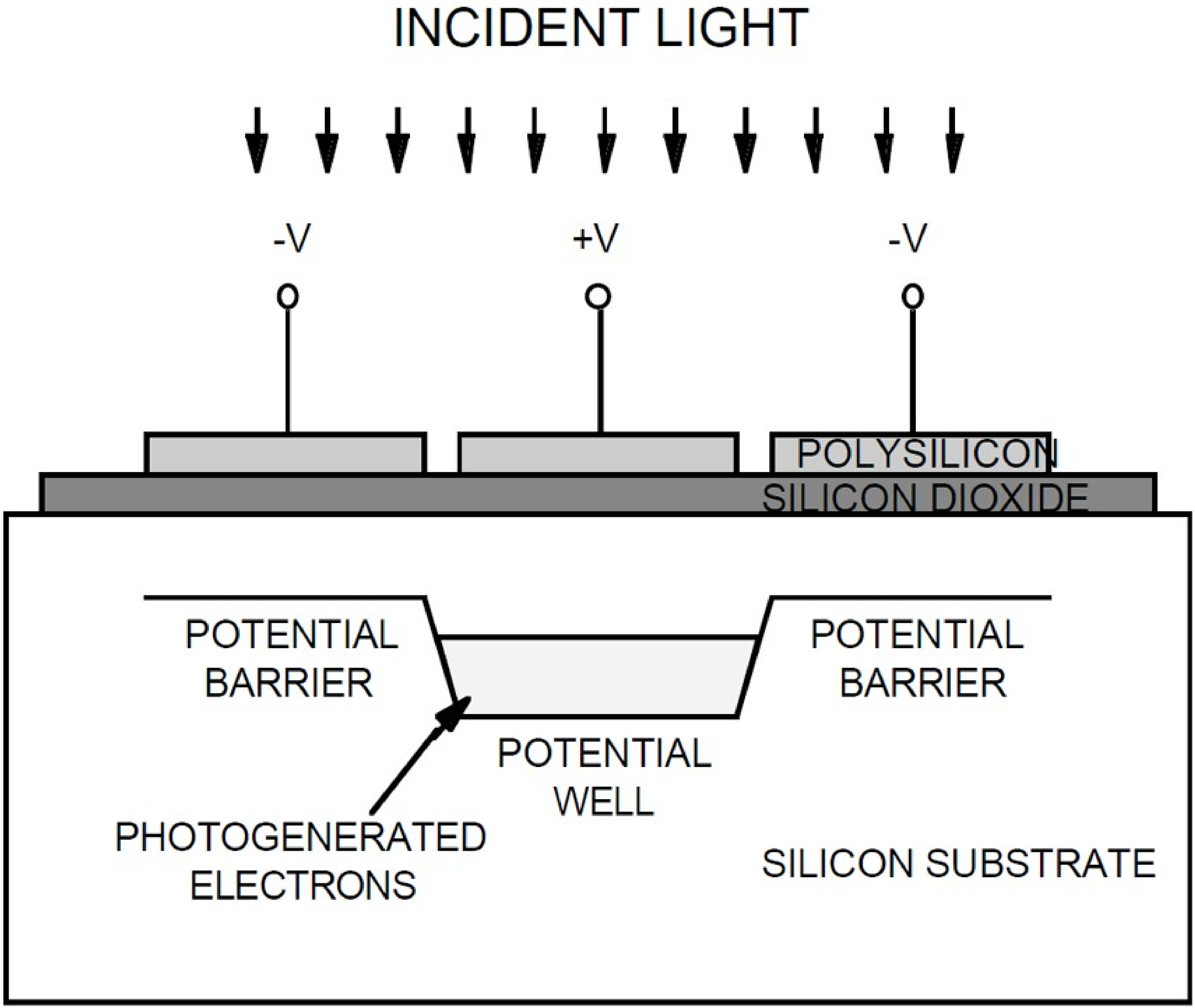


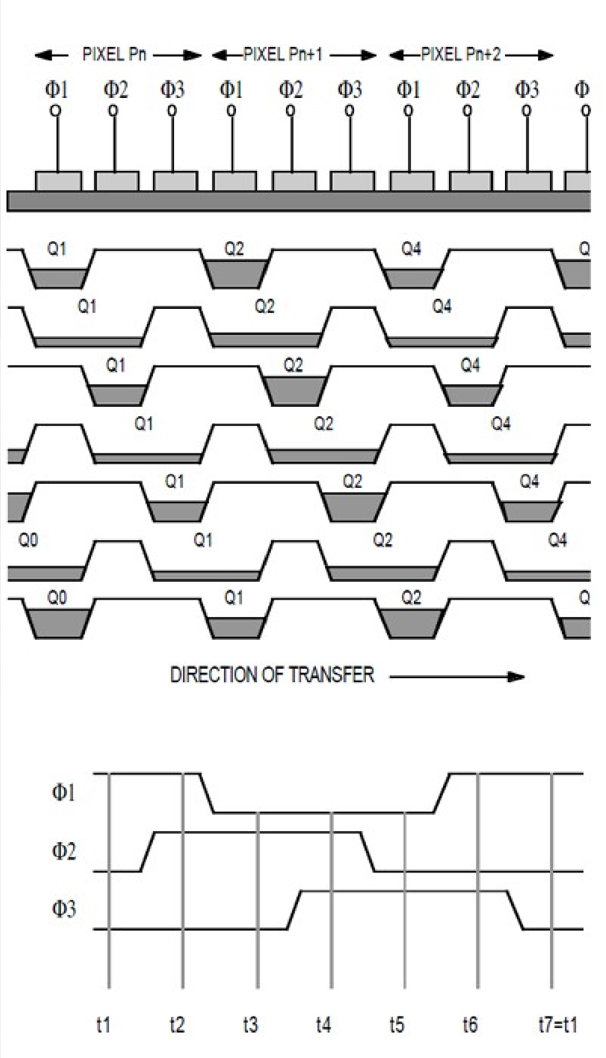
Figure 5

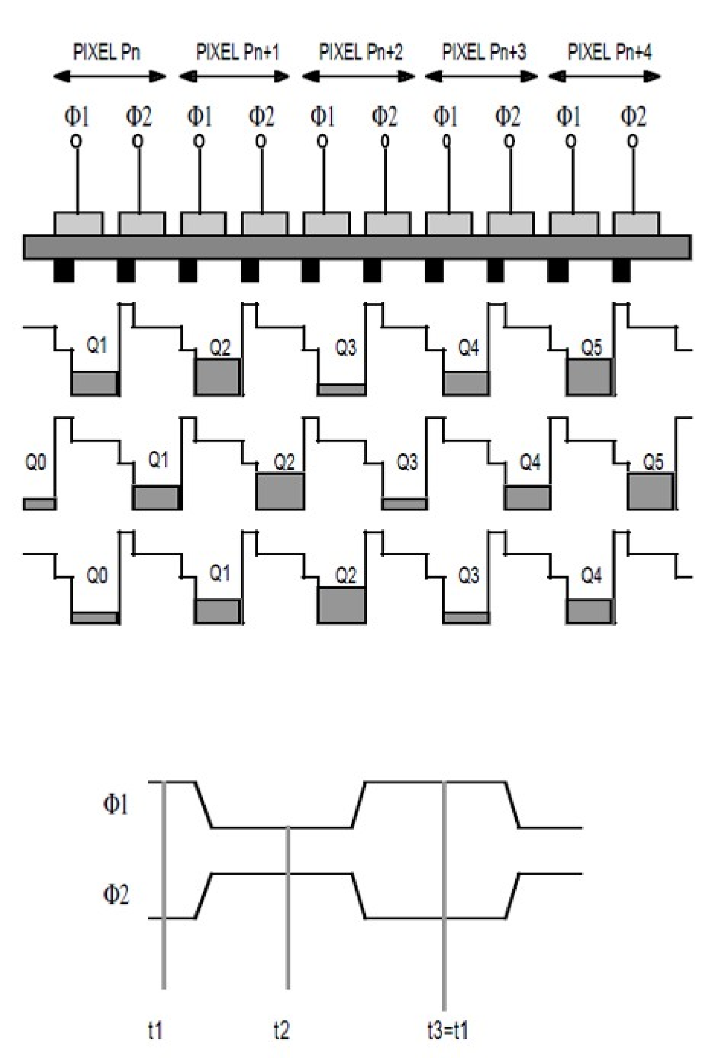
Bucket Brigade CCD Analogy



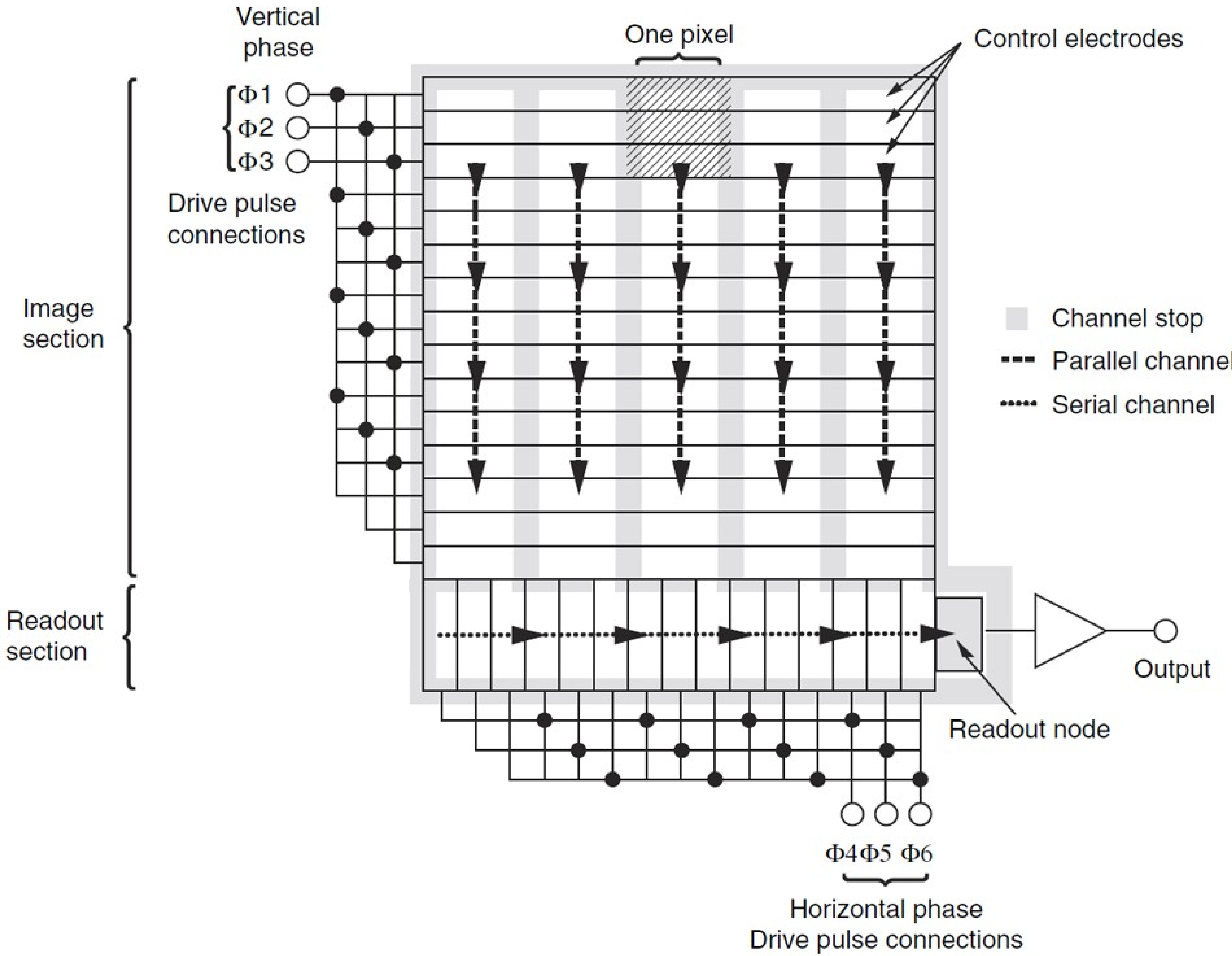

INCIDENT LIGHT
-V
+V
-V
POLYSILICON
SILICON DIOXIDE
POTENTIAL
BARRIER
POTENTIAL
BARRIER
POTENTIAL
WELL
PHOTOGENERATED
ELECTRONS
SILICON SUBSTRATE

Charge "coupling"



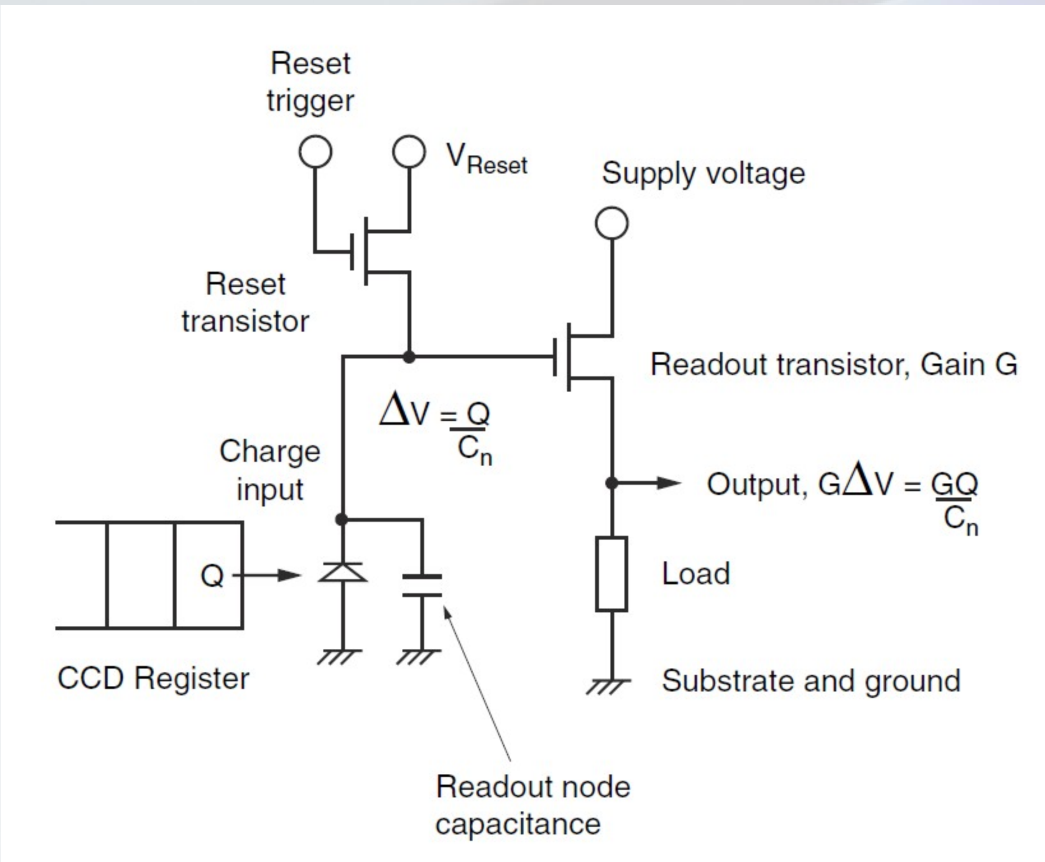


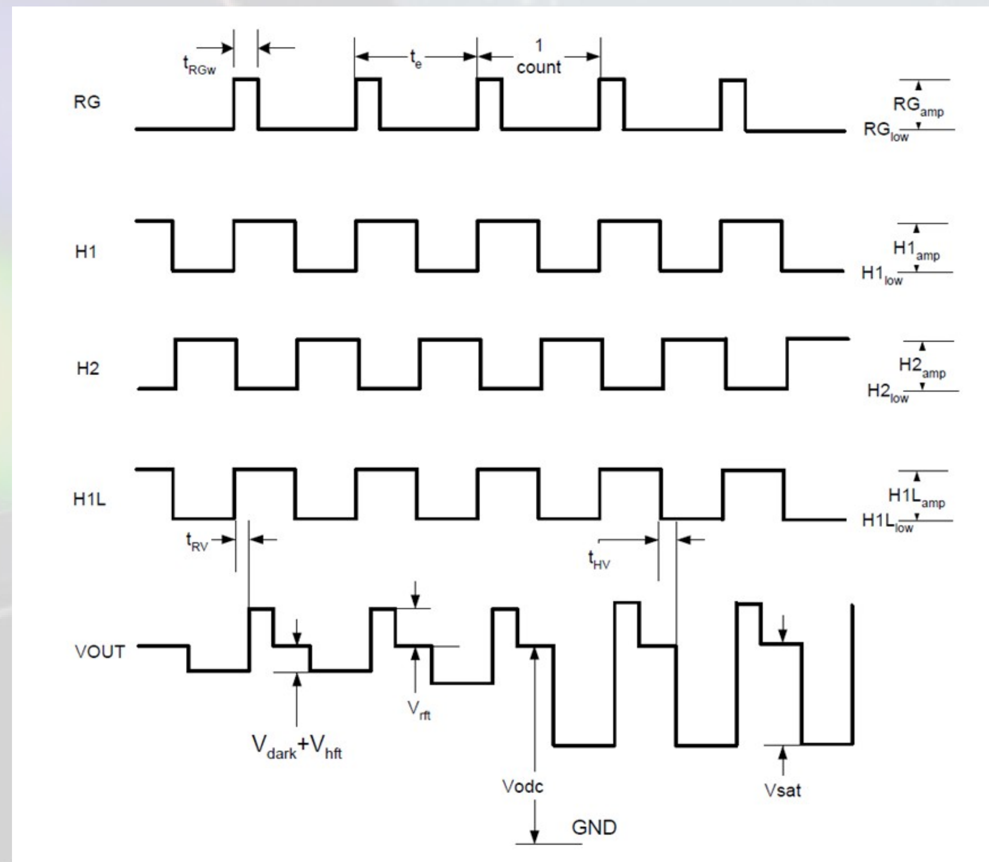
Basic three-phase and true double-phase charge coupling, using step potential under the control electrodes.



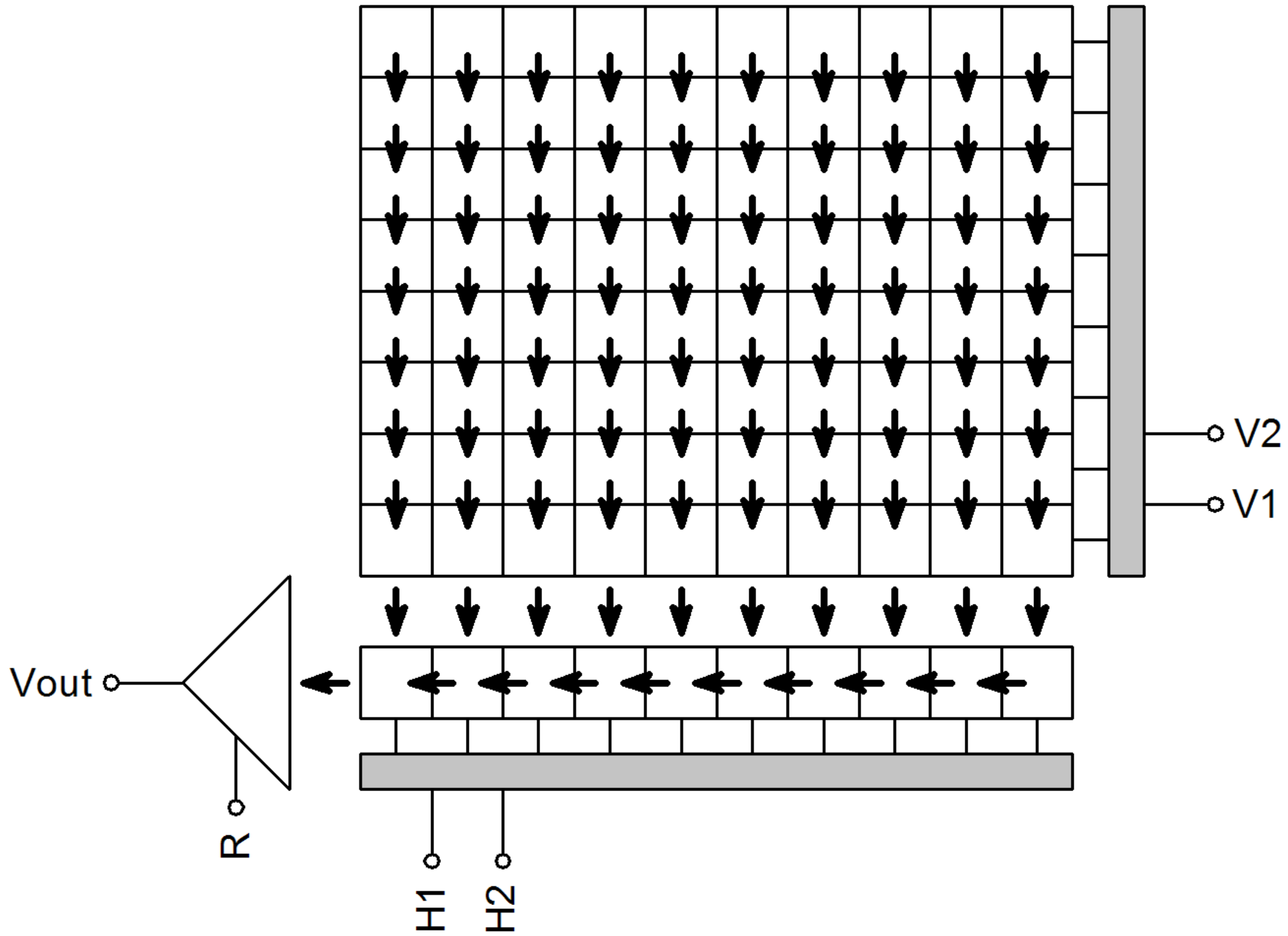
Vertical phase
One pixel
Control electrodes
Φ1
Φ2
Φ3
Drive pulse connections
Image section
Channel stop
Parallel channel
Serial channel
Readout section
Output
Readout node
Φ4Φ5 Φ6
Horizontal phase
Drive pulse connections

Output amplifier (output node), charge-to-voltage converter

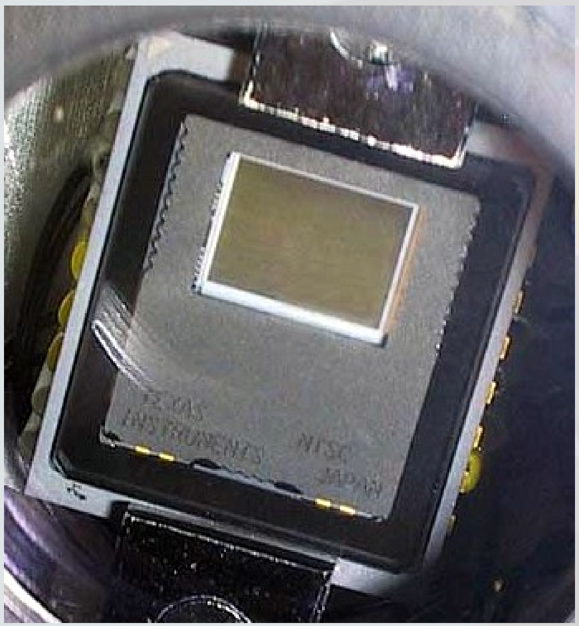


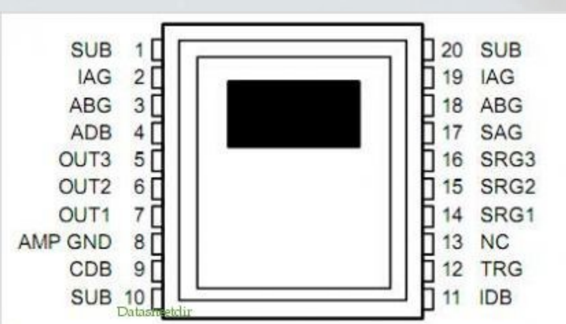


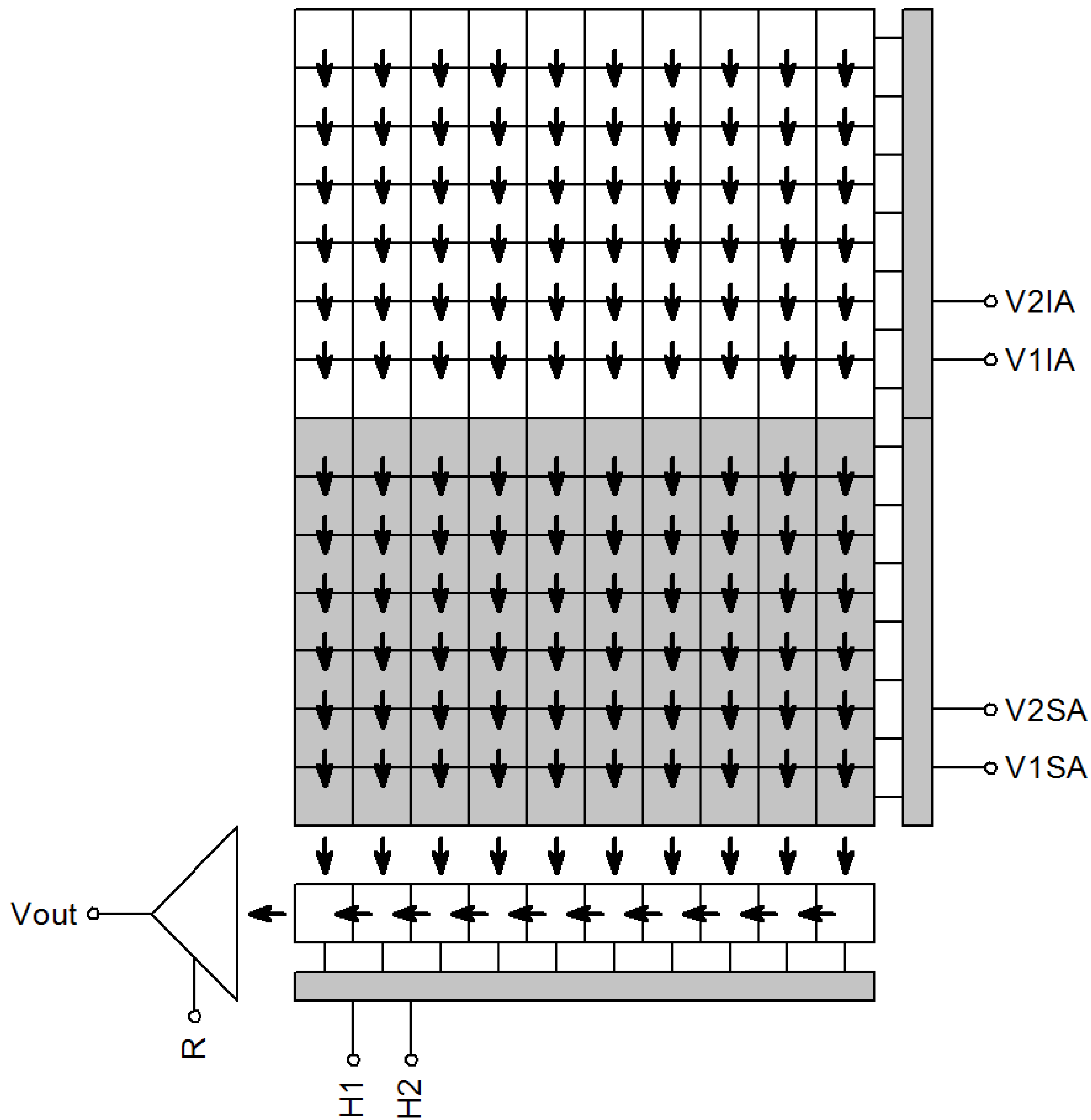
Full Frame (FF) CCD



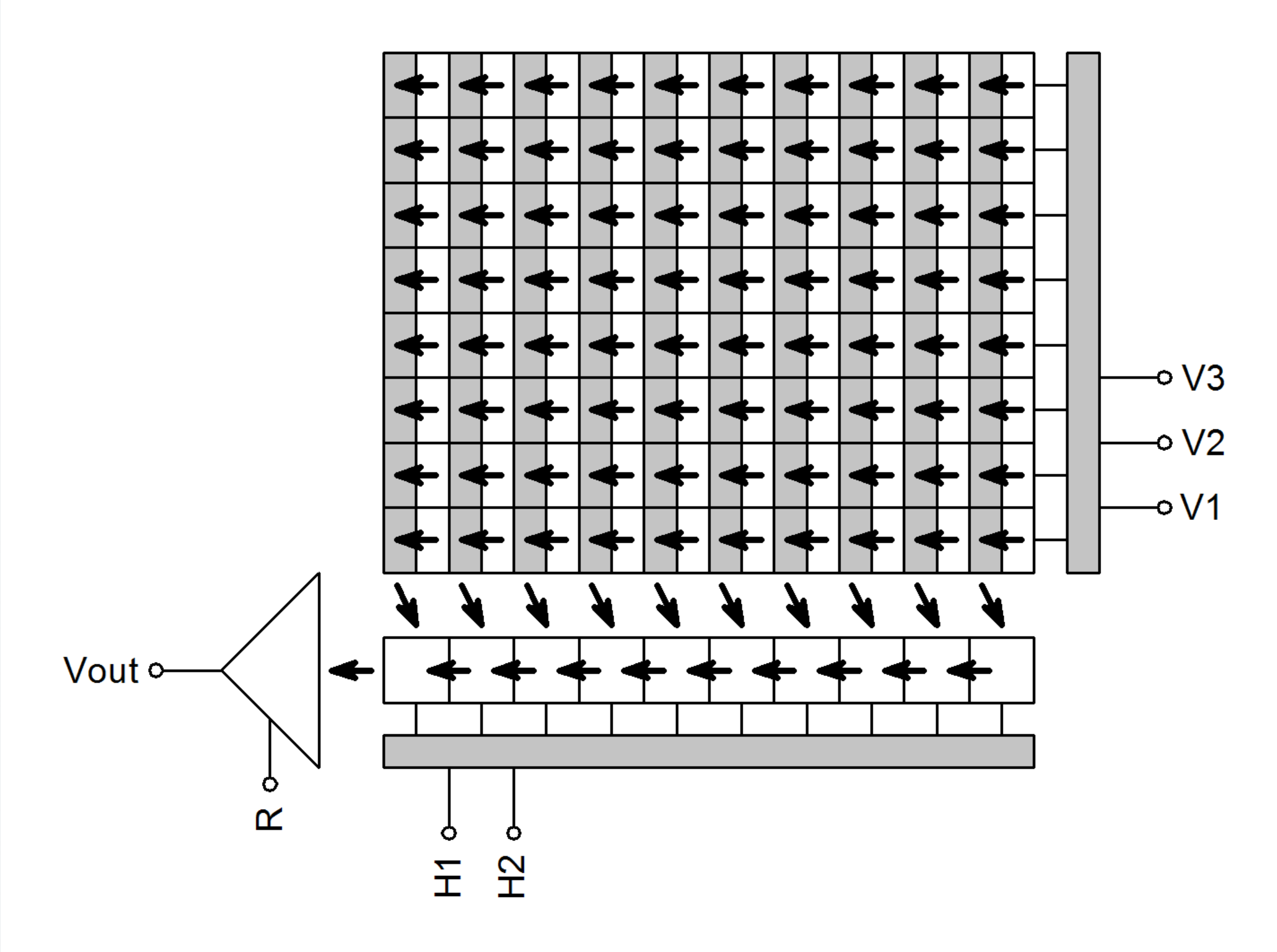
Frame Transfer (FT) CCD





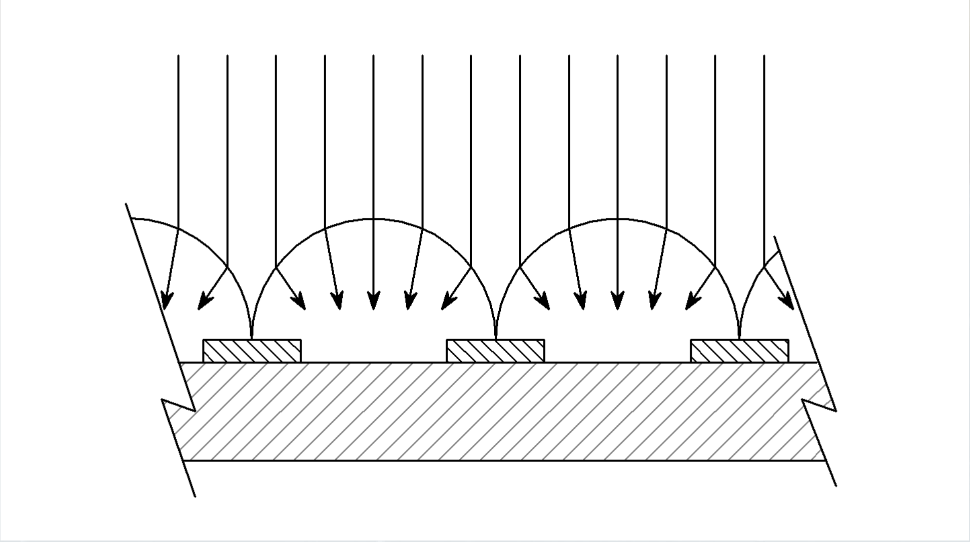


Interline Transfer (IT) CCD



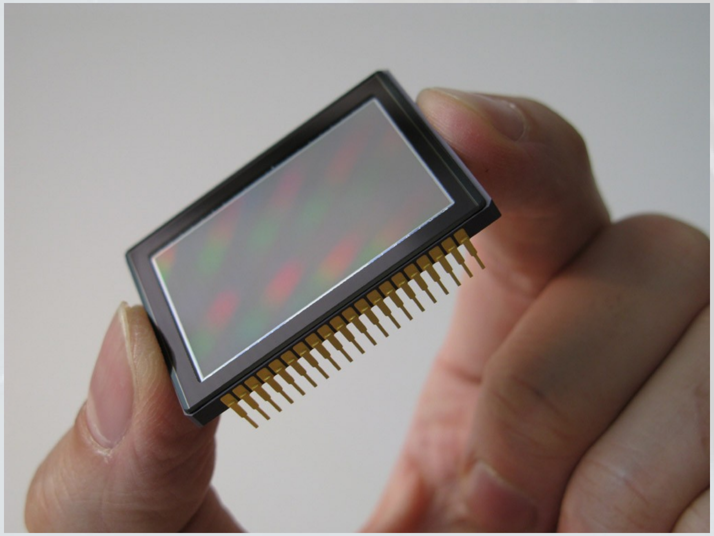
Fight for a quantum efficiency (micro-lenses)

- Interlacing of active and inactive (shielded) columns limits the area used to collect light. This effect can be partially compensated by advanced manufacturing technologies, e.g. by using of so-called micro-lenses.
- Micro-lenses focus light from areas shielded by inactive portions of a CCD (shielded vertical columns) to active light-sensitive areas.



KAI-11002 quantum efficiency

- With micro-lenses (top)
- Without micro-lenses (bottom)



Monochrome with Microlens Quantum Efficiency

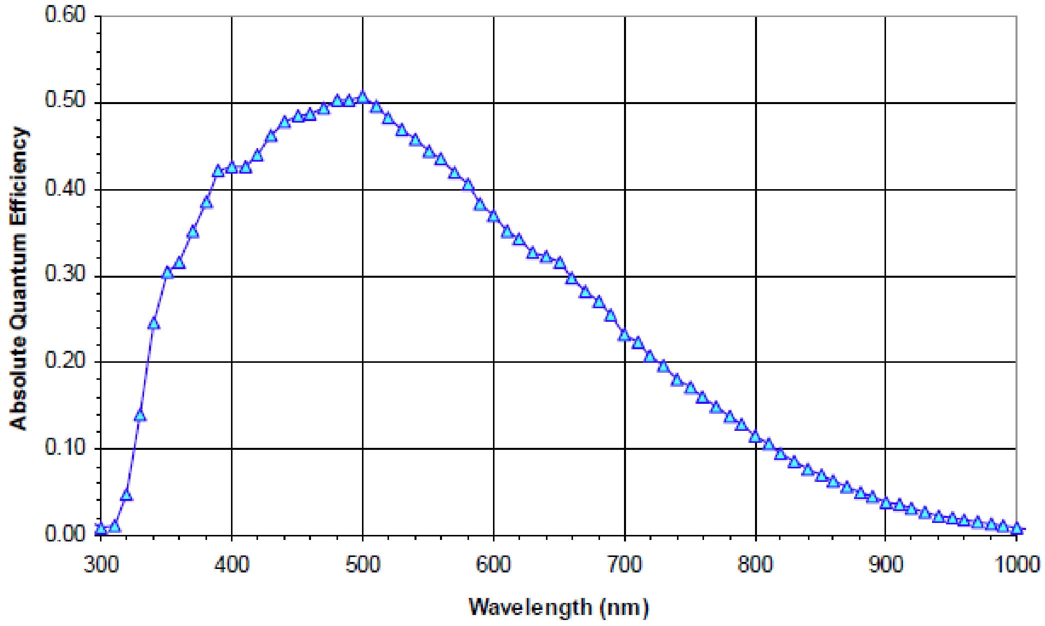


Figure 12: Monochrome with Microlens Quantum Efficiency

Monochrome without Microlens Quantum Efficiency

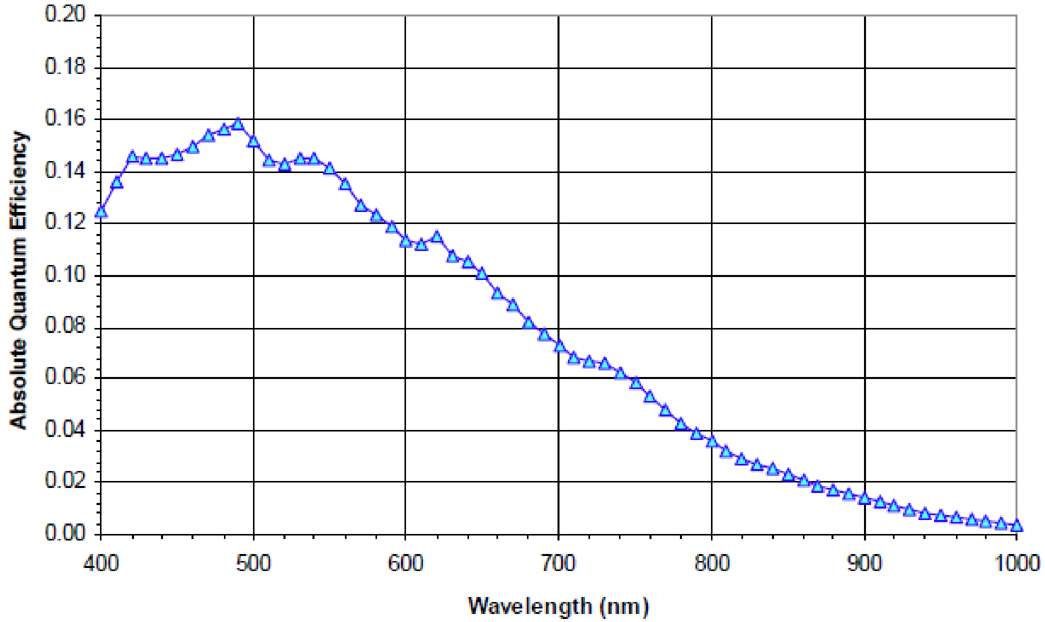
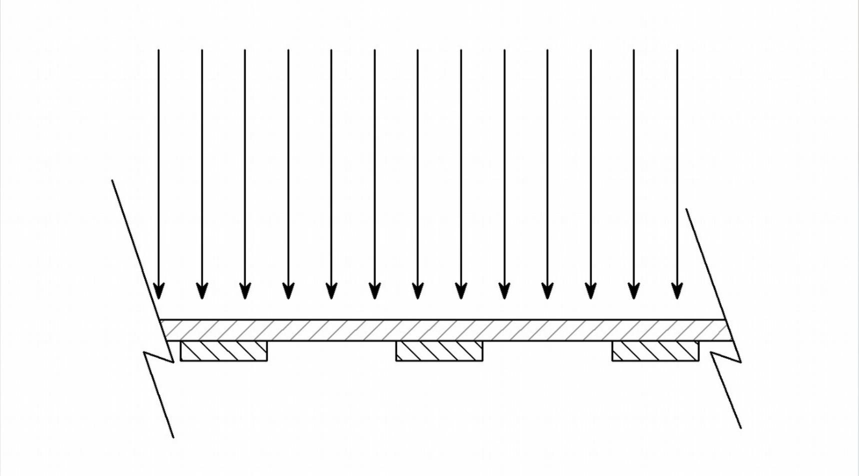


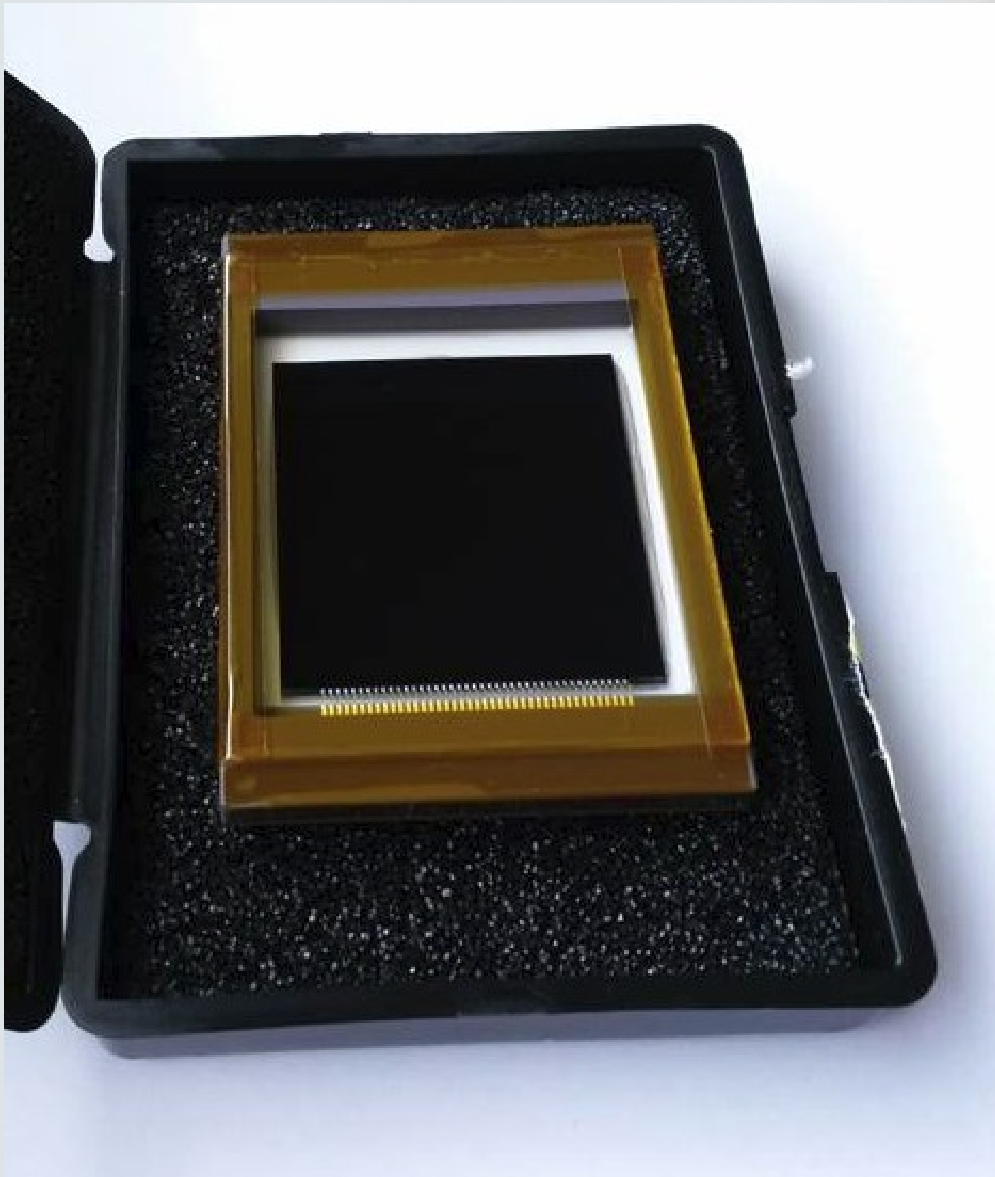
Figure 13: Monochrome without Microlens Quantum Efficiency

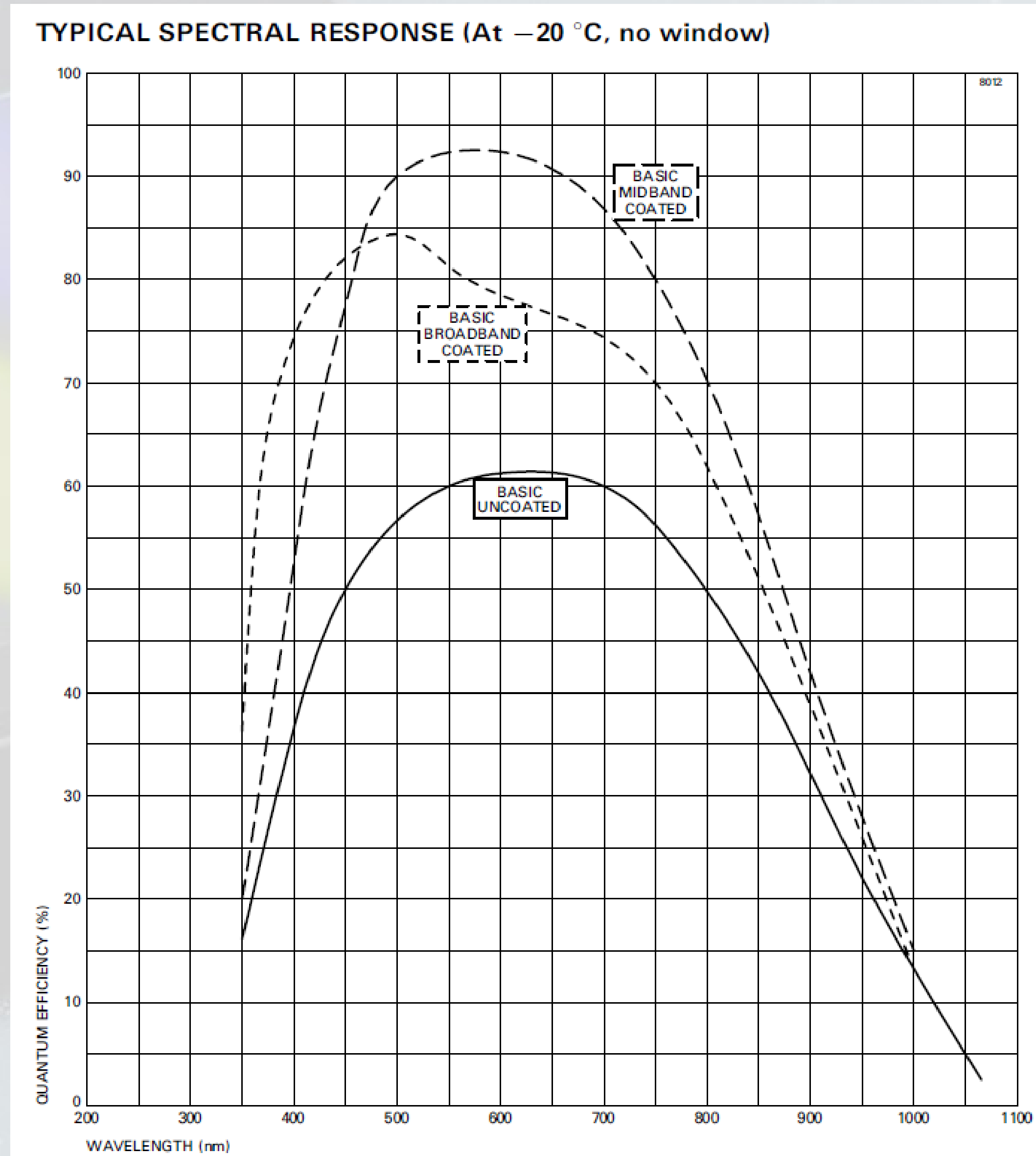
Fight for a quantum efficiency (Back-illuminated CCDs)

- The highest possible QE can be achieved by using a thinned CCD detector, illuminated from the back side.
  - Such chips are packaged “upside-down”, so the electrodes are on the bottom side and do not block the incoming light.
  - The CCD silicone itself is very thinned up to a thickness of a few micrometers.
  - Almost complete CCD back side is exposed to incoming light.



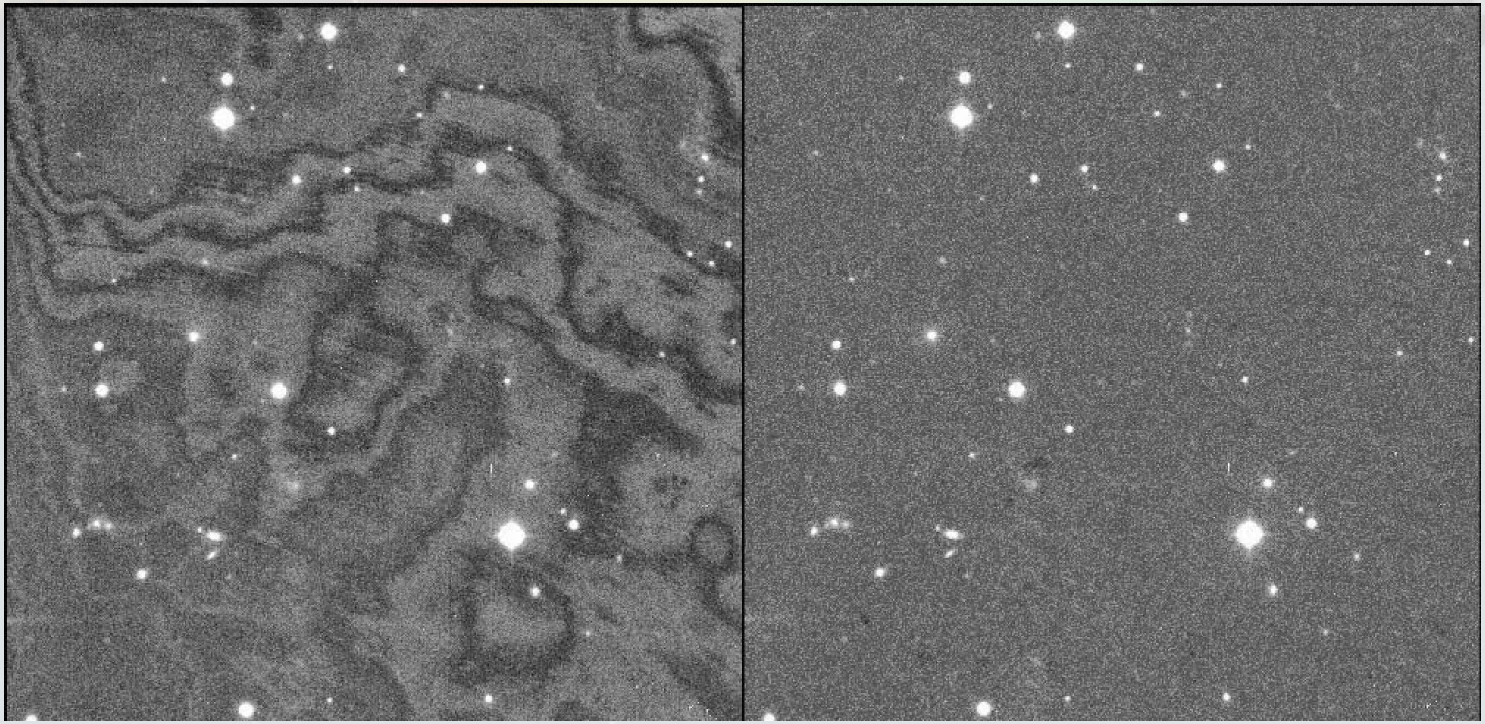
The E2V back-illuminated CCD





Back-illuminated CCDs

- Manufacturing of the thinned detectors is demanding and these CCDs are very expensive (really VERY expensive).
- Illumination from the back side also causes some negative effects, like e.g. interference patters caused by infra-red light of the atmosphere (effect called “fringing”).

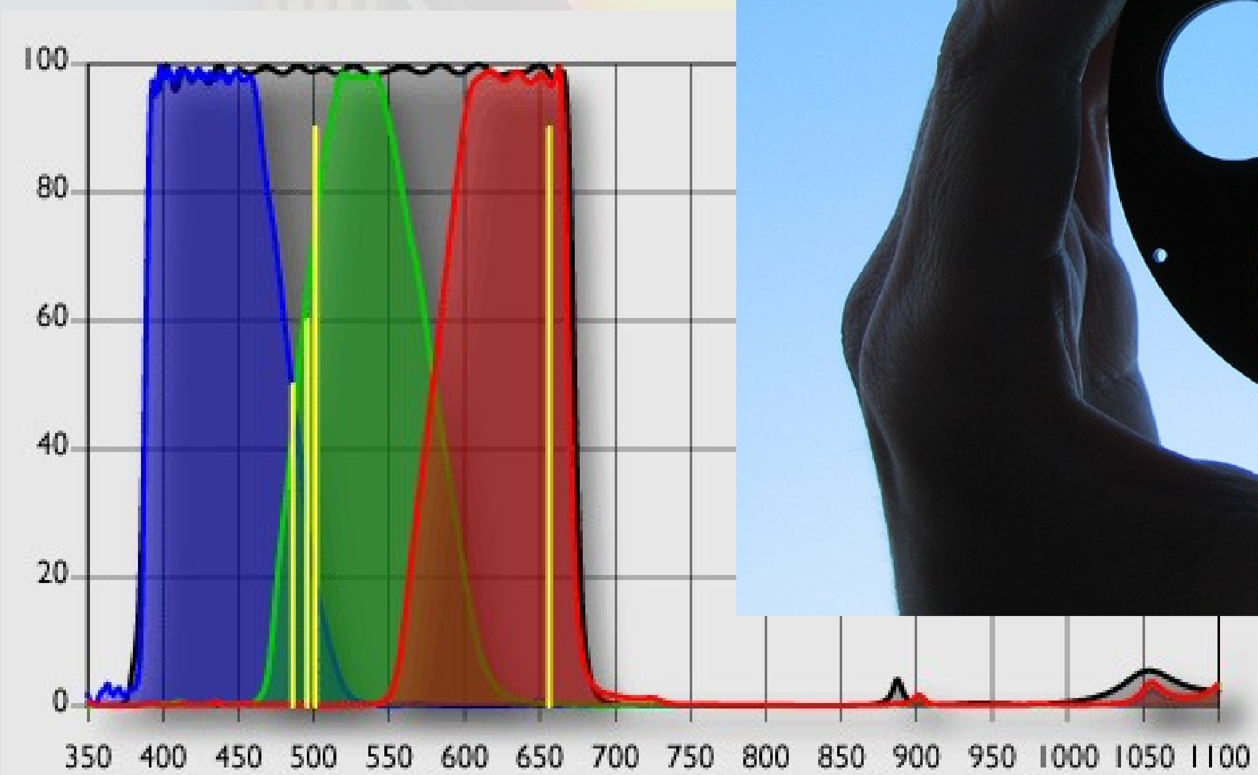


Color CCD detectors

Color images

- It is necessary to acquire three images in three colors – red, green and blue – to create a color image. But CCD detectors are sensitive to all visible wavelengths up to near-IR portion of the spectrum. So it is necessary to use filters to limit the captured image to a single color only.
- There are two basic ways how to create color image:
  - It is possible to perform individual exposures using monochrome detector through the red, green and blue filters.
  - It is also possible to apply filters directly to the CCD pixels. Color image can be then obtained using single exposure only.

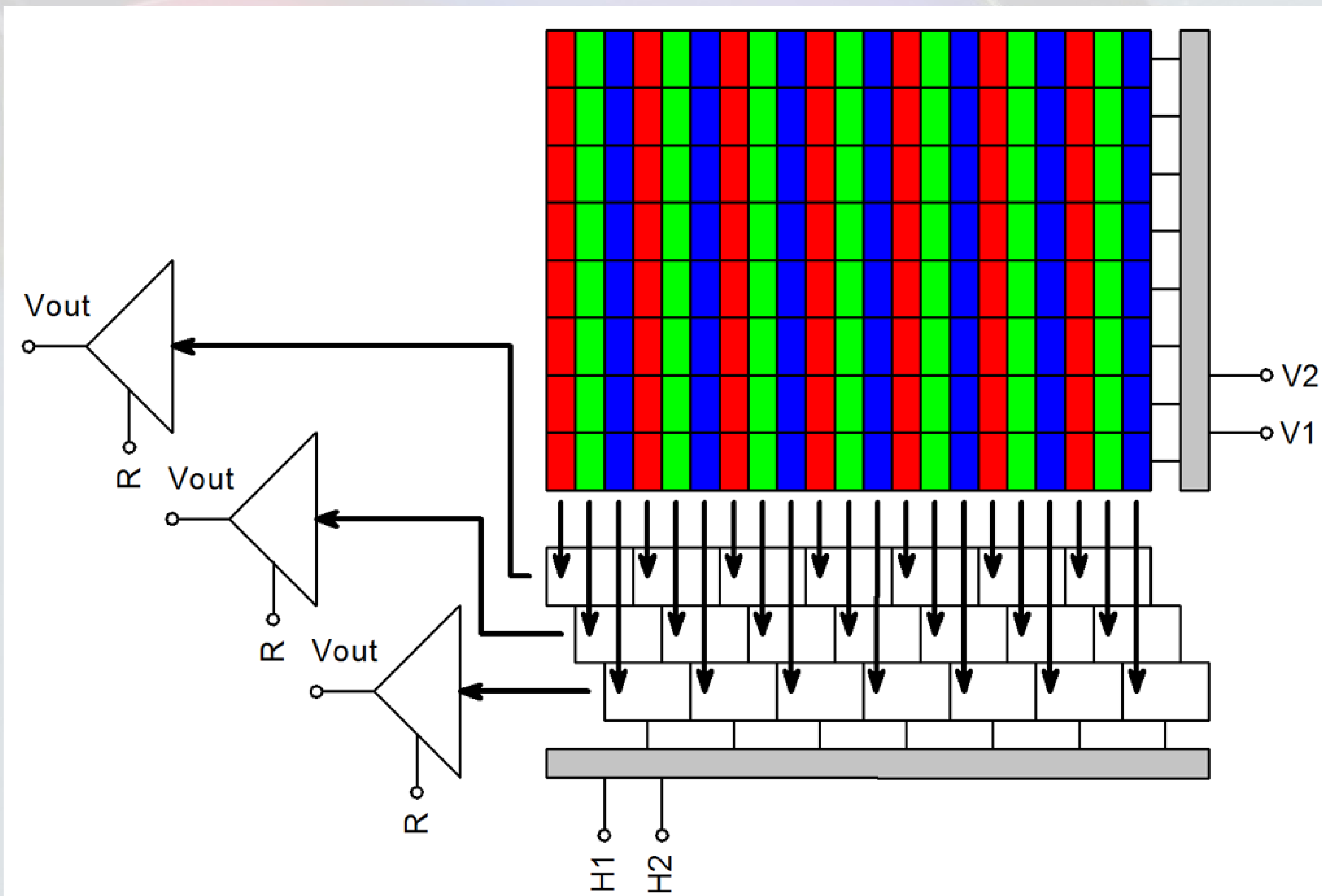
RGB filters for monochrome CCD




Red
Green
Blue

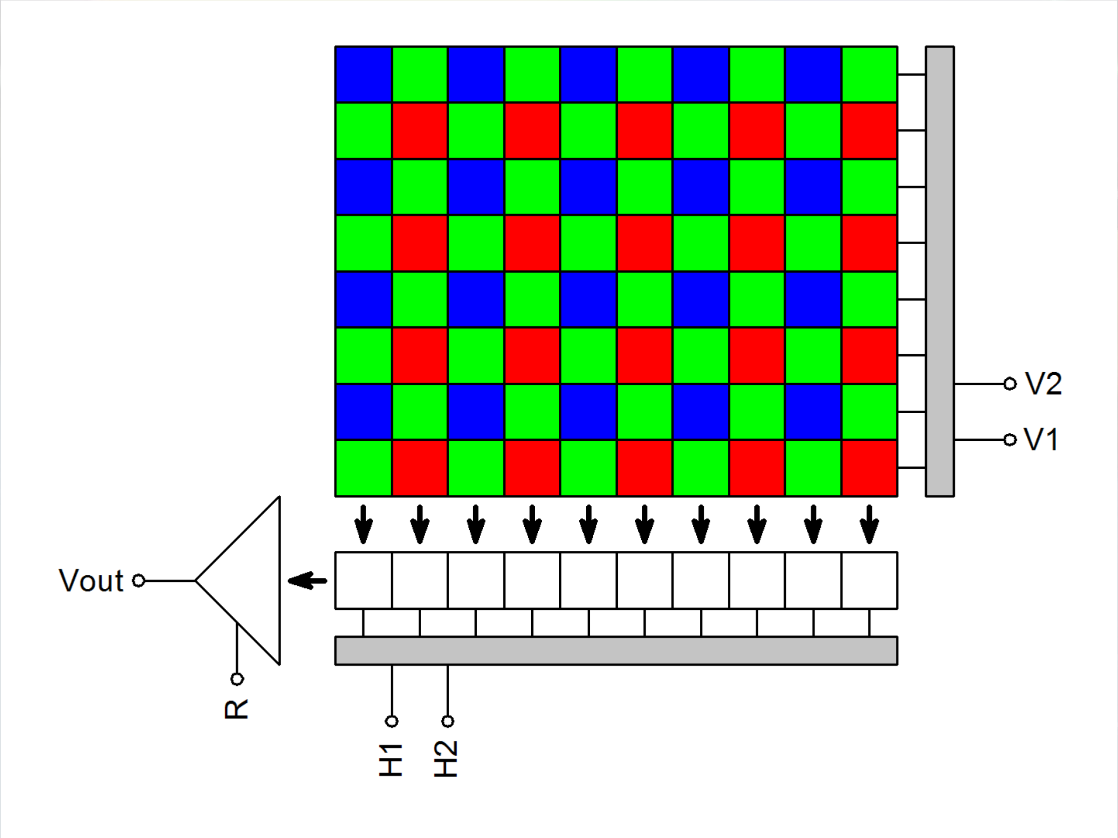
Color CCD sensors

- The early color CCD sensors worked with the whole column of pixels covered with one color mask.

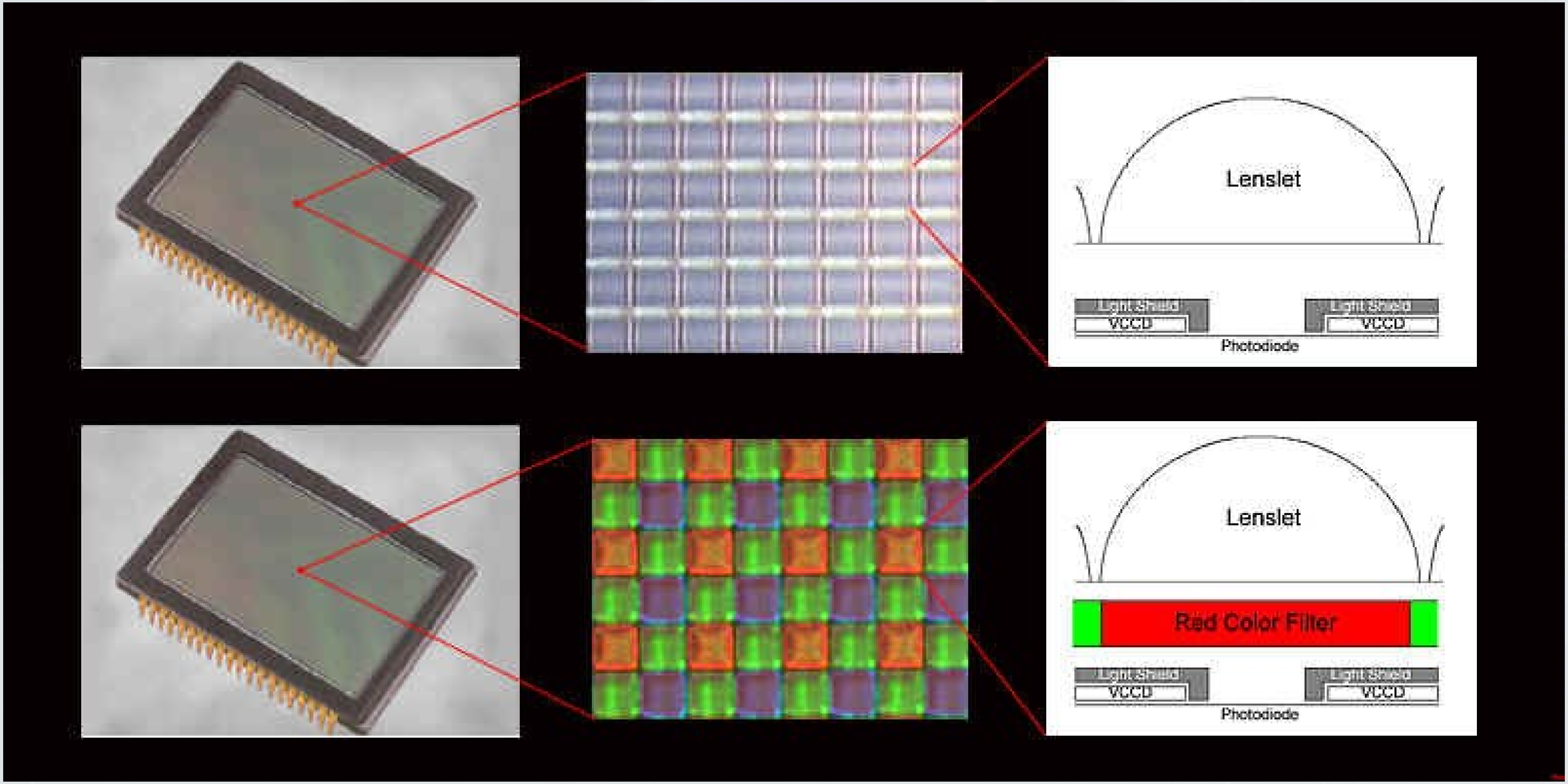


Color CCD sensors (2)

- Current color CCD detectors use so-called "Bayer mask". Mr. Bayer, as a Kodak employe, came with an idea of color mask, which is currently used in almost every color CCD or CMOS detector.

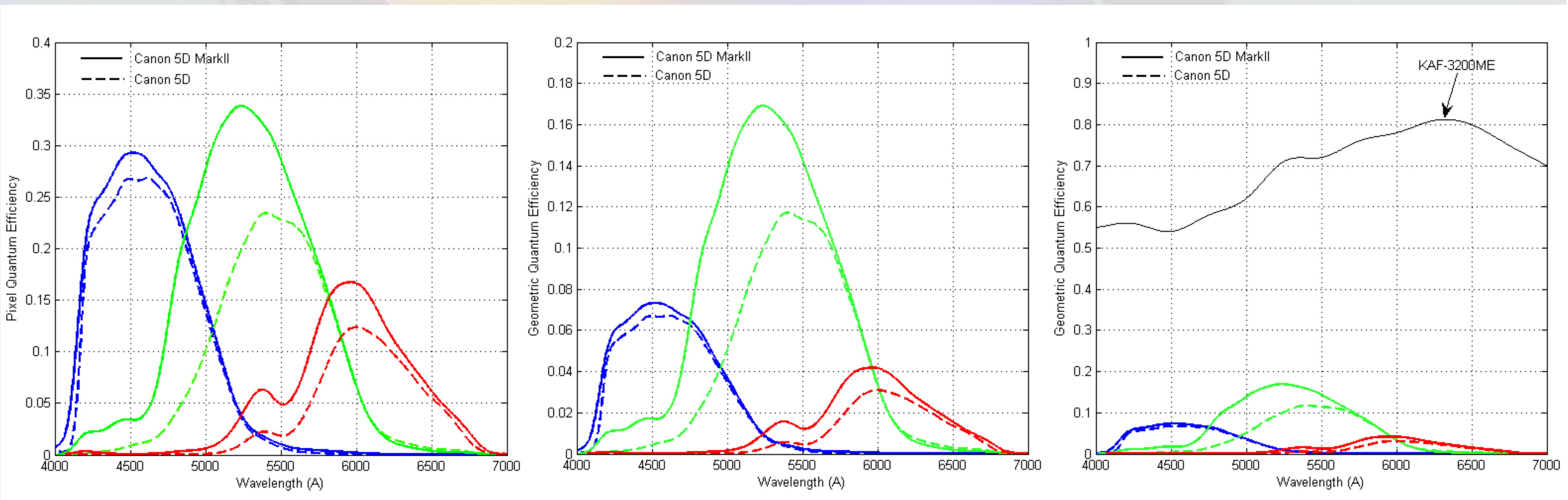


KAI-11002 CCD detector in monochrome and color versions

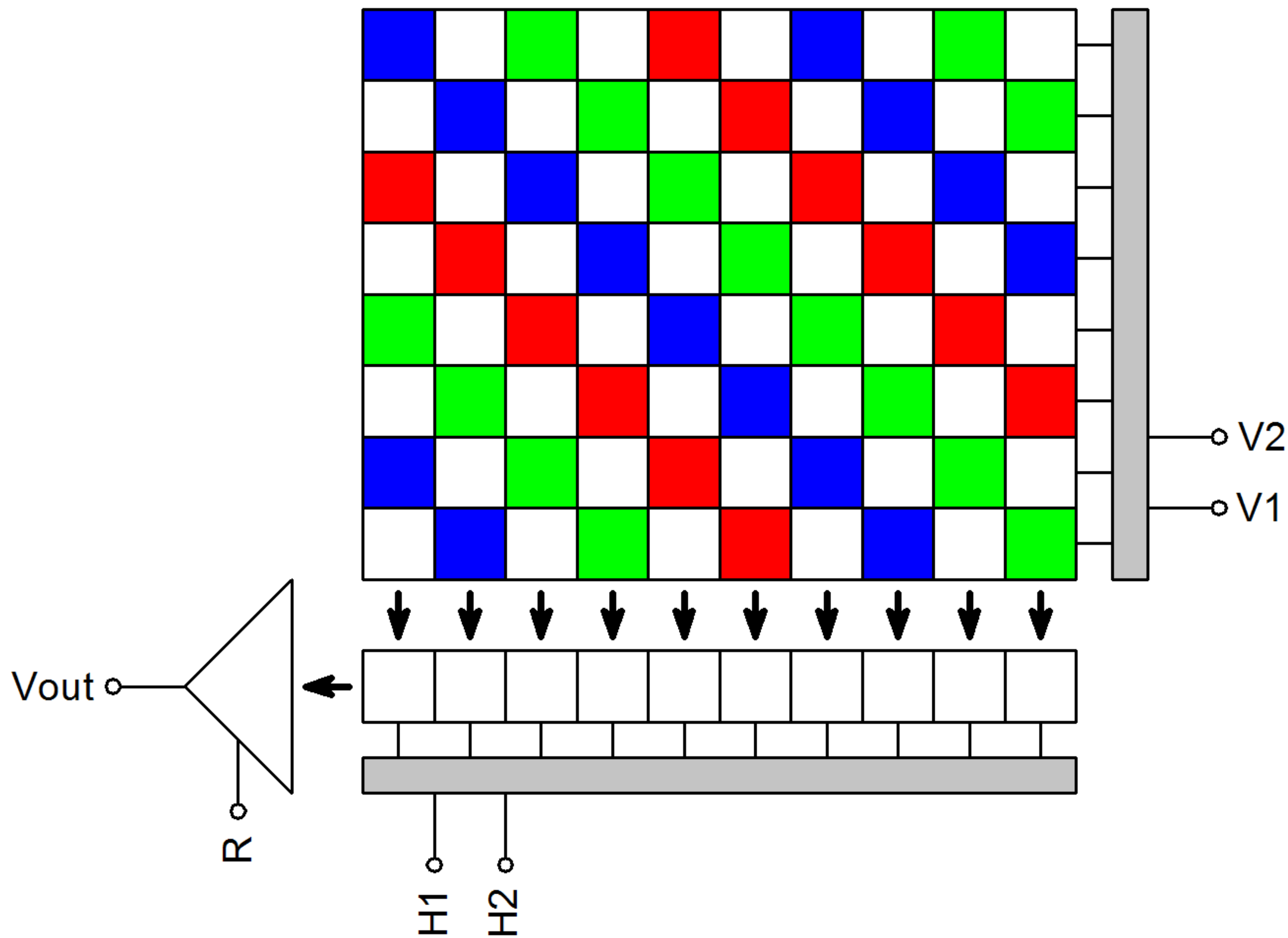


Spatial resolution and quantum efficiency limitations

- Comparison of a pixel and geometric quantum efficiency of a DSLR (Canon EOS 5D) and CCD camera (KAF-3200ME):



Sparse Bayer Mask



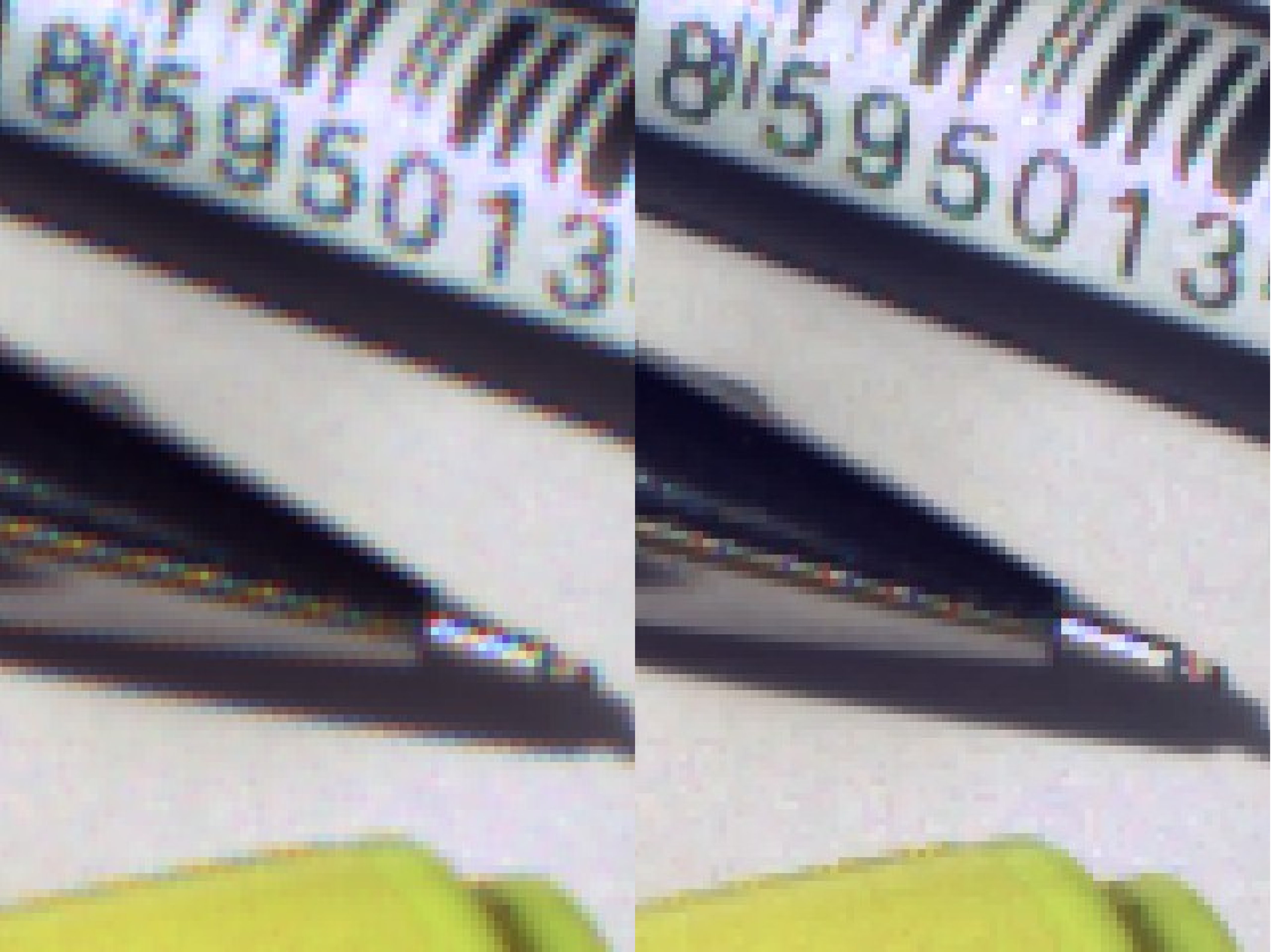
Color and luminance channels

- Processing of color CCD image relies on the fact, that human's eye is much more sensitive to changes in image brightness compared to changes in color.
- Bayer mask almost keeps the detector resolution in the luminance – it is possible to calculate it for each pixel from the color information of surrounding color pixels with only a small error.
- Color information is calculated from surrounding pixels with higher error, but human's eye does not distinguish it.

Raw image from a color CCD (with Bayer mask)

Color image reconstruction

- There are many ways how to calculate missing color information for all pixels.
- Bilinear interpolation provides much better results than simple extending of missing colors to surrounding pixels and it is also simple and fast. But if the optics resolution is good enough to be comparable to the size of individual pixels, color artifacts appear close to sharp edges and small details.
- Multiple-pass methods are significantly slower compared to one-pass bilinear interpolation, but their results are considerable better, especially around small details. These methods allow utilizing of color sensors spatial resolution to their limits.

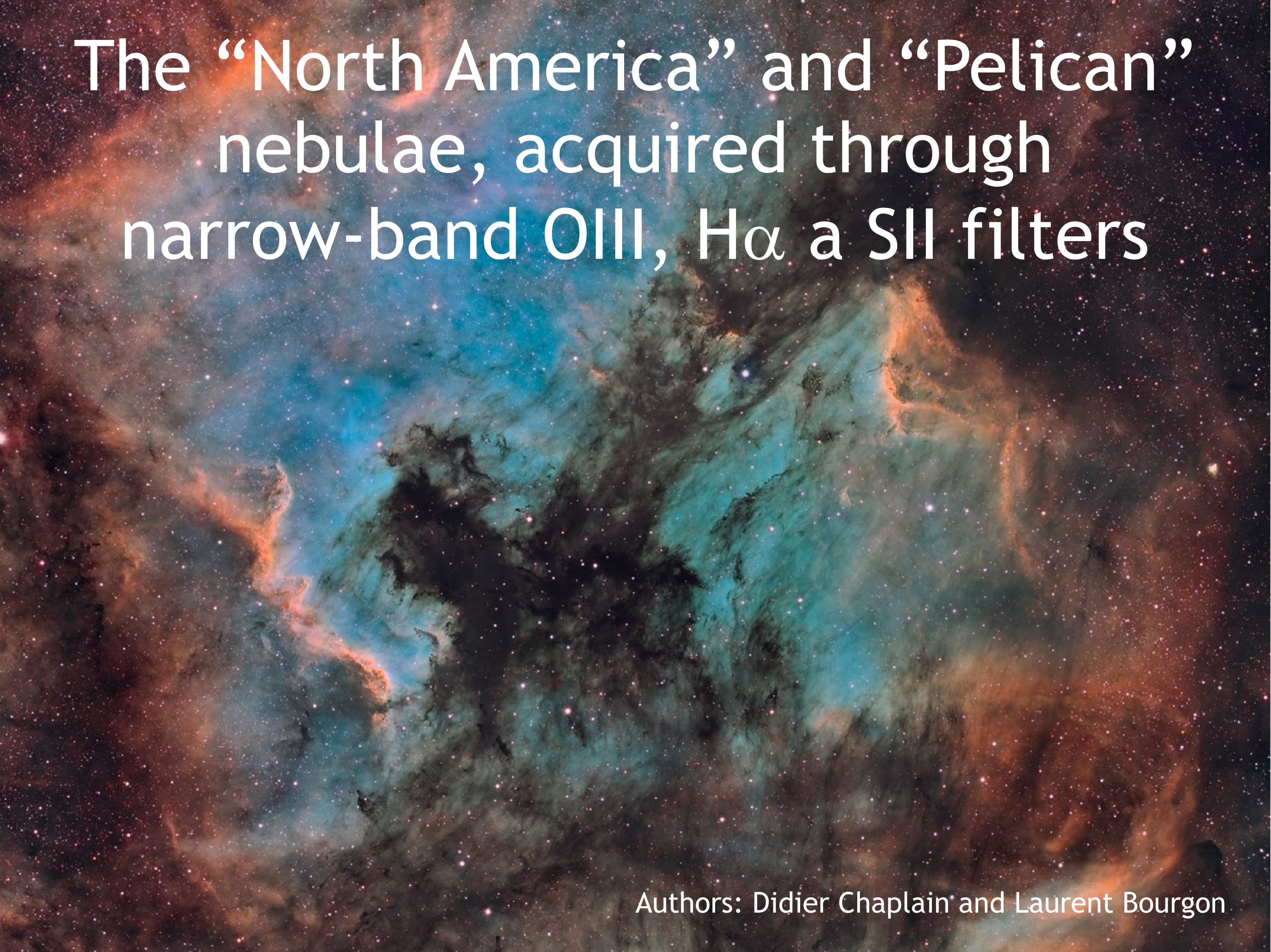


Color and monochrome detectors in astronomy

- Although the color CCDs are perfectly suitable for still and video cameras, astronomers use them only exceptionally.
  - They are used mainly by amateur astronomers, interested in imaging of pretty images of deep-space objects with the lowest possible efforts. But majority of amateurs, as well as all professionals, use monochrome detectors, possibly matted with individual color filters.
- Monochrome detectors are generally more suitable for applications in astronomy from number of reasons:
  - First, monochrome CCD can create color image with the usage of color filters. Such image is typically of better quality compared to image acquired with color detector.

- Color detector on the other side can create monochrome image only at the cost of lower resolution and sensitivity.
- Color CCD has one fixed color mask without the possibility to use various other filters or no filters at all.
  - Many applications benefit from capturing images without filters, with maximum possible quantum efficiency.
  - Other applications require imaging in some specific wavelength.
  - Monochrome detector can acquire narrow-band images in the Hα, OIII or SII lines etc.
  - Professionals prefer standardized Johnson (U)BVRI filters for photometric measurements instead of RGB passbands used for astrophotography etc.
- Color CCDs have lower QE compared to monochrome ones. Limiting of the QE by color filter from around 80% to around 25% wastes precious light.

The “North America” and “Pelican” nebulae, acquired through narrow-band OIII, $H\alpha$ a SII filters

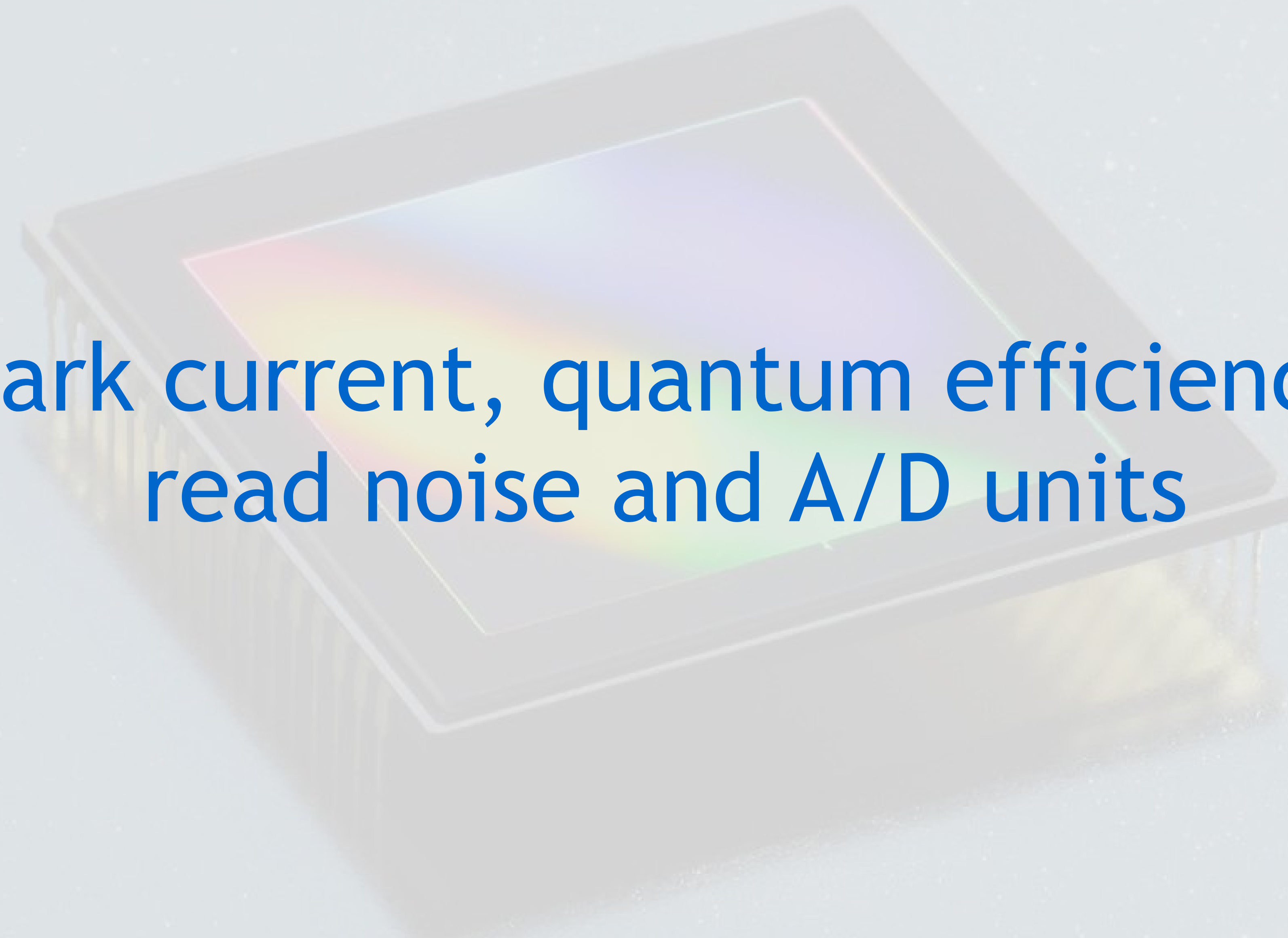


Authors: Didier Chaplain and Laurent Bourgon


The Sun in the Hα line
(false colors)
Author: Martin Myslivec

- Compact camera and mobile phone lenses quality is limited, so the smallest details cover multiple pixels on the sensor. One pixel is not that important.
  - This is not true in astronomy. Star on the CCD typically cover only a few pixels. Interpolation of color from surrounding pixels introduces significant errors and prohibits precise measurement of position ad brightness.
- Color CCD detectors do not allow usage of binning. Binnig would mix pixels with different filters and the color information would be lost.
  - There are color sensors, allowing binning even with Bayer mask applied, only pixels of the same color are binned. But the CCD layout is rather complex and electrodes cover significant portion of the detector. This is why such detectors are only rare.

- Color CCD detectors do not allow so-called Time-Delay Integration (or Drift-Scan Integration).
  - Image is vertically shifted through the detector at the speed synchronized with the movement of the image on the sensor area.
  - Image is then read line by line, in the precisely defined instances.
  - TDI allow capturing of long strips of the sky, which width is defined by the width of the sensor and the strip length depends only on the total integration time. Image movement on the detector is typically defined by Earth rotation.
- Monochrome detectors can capture color images not only through RGB filters. It is possible to combine high-quality, hi-resolution monochrome image (luminance) with color exposures acquired at lower resolution and with worse S/N. This technique is called LRGB imaging.



Dark current, quantum efficiency, read noise and A/D units

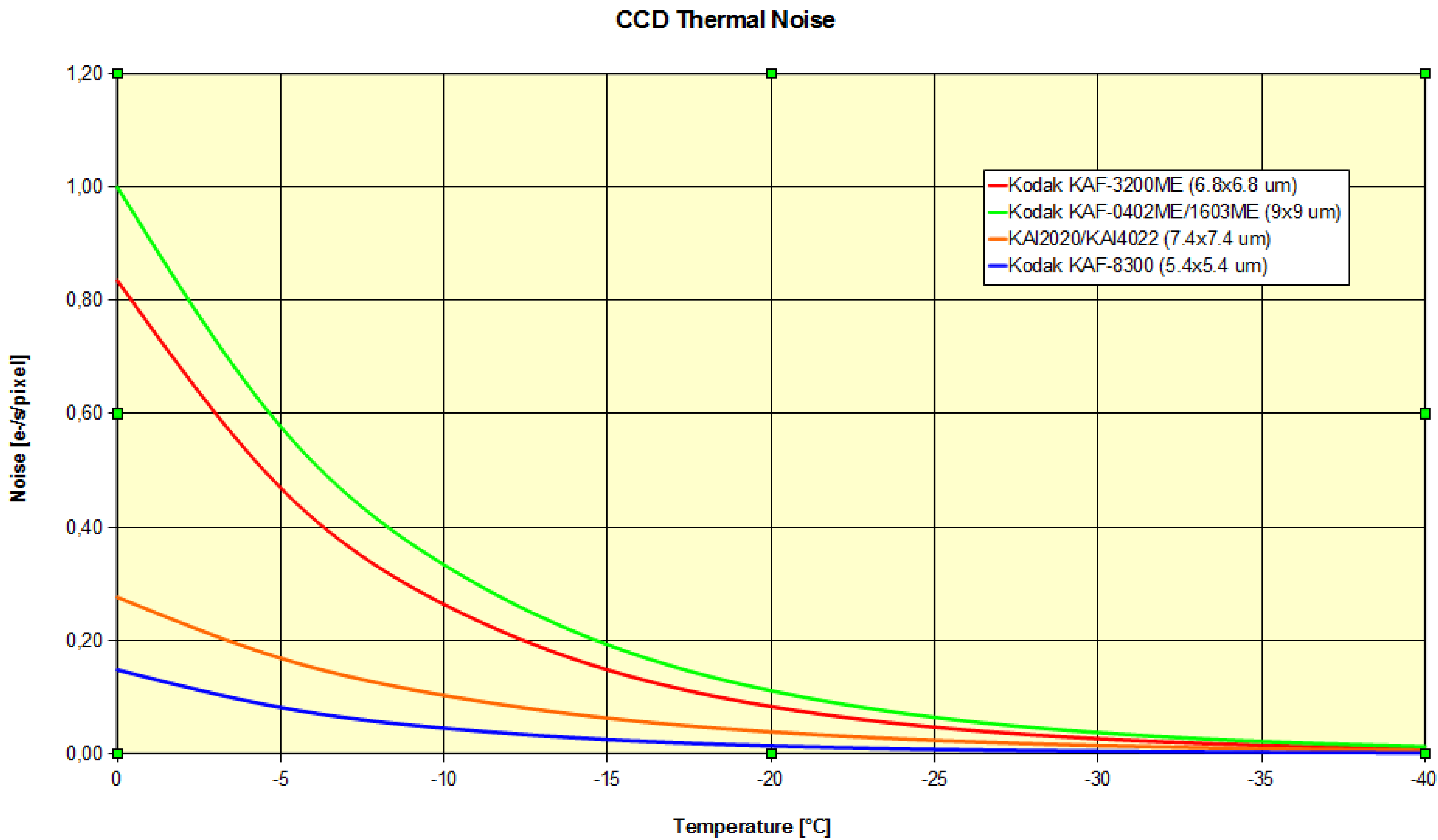
Dark current

- CCD technology disadvantage is the fact, that electrons are excited not only by the incoming light, but also randomly with dependance on the detector temperature, pixel size and manufacturing technology. Such randomly created charge is called “dark current” (it generates signal, even if the detector is completely in darkness).
- The dark current is usually expressed in electrons per second per pixel at the defined temperature. For instance the CCD detector OnSemi (Kodak) KAF-1603 generates1 e–/s per pixel at 0°C.

Dark Frame – image of the dark current

- The dark current plus side is that it remains constant at the defined conditions (or at last very similar).
  - Each image, read from the CCD camera, contains both the signal generated by detector illumination and the signal generated by the dark current.
  - It is possible to perform the same exposure once again, but with shutter closed. Such image would contain only the signal generated by the dark current – this is why it is called the Dark Frame.
  - Then it is possible to subtract the Dark Frame from the light image and thus to eliminate the portion of the image generated by the dark current (this procedure will be described later, when we discuss image calibration).

The dark current of some CCDs



Other sources of noise in CCD

- The dark current is not the only source of the unwanted signal.
- No electronics can work without noise. The so-called Read Noise is inherent for every CCD type and it is usually expressed in electrons RMS.
  - For instance the above mentioned OnSemi (Kodak) KAF-1603 CCD read noise is 15 e– RMS. Simply put, it is not possible to read an image from this CCD with lower noise than 15 e– RMS, regardless of the temperature.
  - The CCD output voltage is digitized by the camera electronics, which also introduces certain noise level. Very good electronics noise is so low, that CCD read noise dominates and the whole system read noise almost equals to the read noise of the CCD.

Electrons, volts and the ADUs

- Camera read noise is usually expressed in electrons, but electronics noise is often expresses in volts RMS.
  - The relation is simple: every CCD chip (it output node) is characterized by the conversion ratio “volts/electron”. E.g. the KAF-1603 output node converts 1 electron to the voltage 10 μV.
  - The result of CCD read process is a matrix of numbers, each representing one pixel. These numbers are generated by the Analog-to-Digital Converter (ADC).
  - Actual values of the numbers are defined by conversion ratio expressed in electrons per “ADU” (Analog to Digital Unit). So 1 ADU represents one count of the ADC output.

CCD camera gain

- Let's calculate the ratio in e-/ADU for a hypothetical camera:
  - The camera is equipped with a 16-bit ADC with input voltage range 2 V. This means that 2 V input signal is divided into 65 536 units. 1 unit represents voltage 2 V / 65 536 = 30.5 μV.
  - Let's assume the CCD output node converts one electron to 10 μV.
  - The resulting ratio is (30,5 μV / ADU) / (10 μV / e-) = 3 e-/ADU. This means every 3 electrons in the potential well of the pixel cause +1 of resulting number representing image pixel.
- It is important to emphasize, that these calculations are only statistical, valid for large numbers of electrons and pixels. Many cameras have fractional gain, e.g. 2,3 e-/ADU or 0,6 e-/ADU.

CCD detector dynamic range (pixel capacity)

- Every potential well, representing CCD pixel has a certain maximal capacity, generally dependent on the pixel dimensions.
  - Small pixels (~7 μm) typicaly hold around 50 000 e–
  - Medium pixels (~10 μm) can hold around 100 000 e–
  - Large pixels (~25 μm) can hold around 300 000 e–
- CCD cameras usually employ 16-bit ADC with resolution 65 536 ADUs .
  - It is obvious, that converting 50 000 e– to 65 536 levels is superfluous and 15 or even 14-bit ADC would be sufficient.
  - On the other side converting 300 000 e– to 65 536 levels require gain around 4 or 5 e–/ADU, which is quite appropriate.

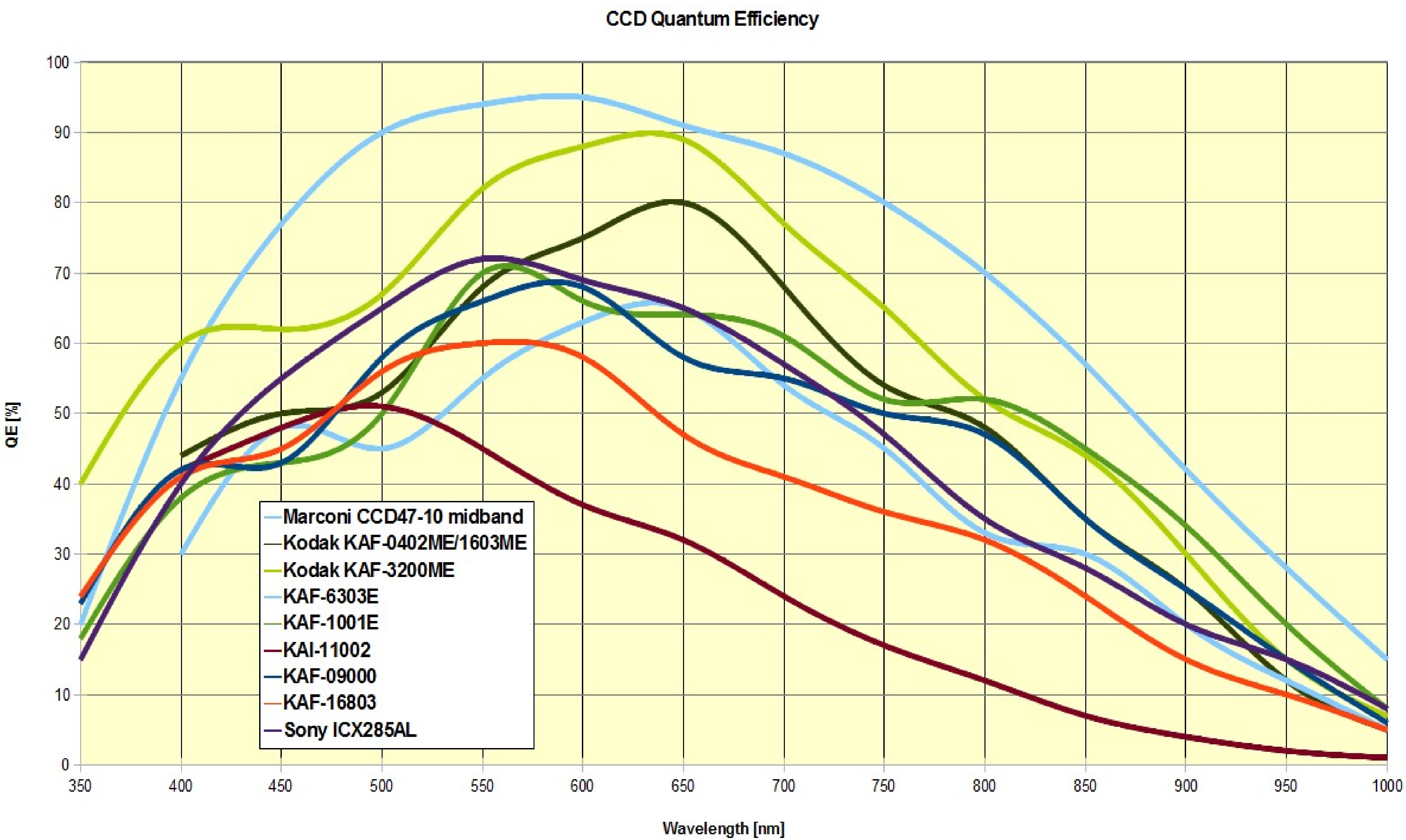
Output node capacity

- Not only every pixel, but also the horizontal register and the output node have a limited capacity of electrons. This must be taken into account especially when we use binning.
  - Let's take for instance KAF-1603 CCD: pixel capacity is 100 000 e–, horizontal register pixel capacity is 200 000 e– and output node capacity is 220 000 e–.
  - Obviously we can use 2×2 binning when no pixel contains more than ~50 000 e–. But if pixels are filled to almost full capacity, vertical binning sums two pixels into horizontal register pixel with up to 200 000 e–, which is the horizontal register limit. But the subsequent horizontal binning sums two pixels into output node, which causes output node overflow.

Quantum efficiency (QE)

- QE is a ratio between the amount of photons hitting the detector and the amount of the generated electrons.
- Data quality is not determined by absolute signal value, but by the signal-to-noise (S/N) ratio. For instance:
  - 10 000 ADU signal with background noise 1 000 ADU RMS results into S/N only 10.
  - 1 000 ADU signal with 10 ADU RMS background noise provides much better S/N 100.
- Noise source is not only dark current and CCD read noise, but mainly sky background – the signal deviation roughly corresponds to the √ of the signal.
  - So the bright sky (e.g. lit by the Moon) degrades precision due to noise (√ of the background), which cannot be removed.

Quantum efficiency (QE)



CCD in astronomy

What CCD detectors bring to astronomers?

- Even the very first CCD detectors offered tremendously higher light sensitivity compared to film, but they suffered from very small image area, high noise, low resolution and high cost.
- All these disadvantages are eliminated today – CCDs offer better resolution, large image area, low noise and their price is continuously falling. Only significant advantages remain:
  - CCD detectors are much more sensitive than film. QE of the CCD/CMOS detectors in digital still cameras vary around 20 or 40 %. QE of the CCD used in astronomical cameras can reach 60 or even 80 % and thinned, back-side illuminated detectors can achieve QE over 90 %. The QE of a very sensitive film varies around 3 or 5 %.

- CCD response to light is linear (as opposite to films). Linear response is a key for precise photometric measurements. When comparing signal (pixel values) of two stars on the CCD image, we can rely on the fact that star fluxes are in the same ratio as pixel values.
- Silicone chip, on which the CCD is manufactured, has very stable mechanical dimensions. Well defined and invariable dimensions allow performing of astrometric measurements.
  - The star (or minor planet, supernova, etc.) position can be measured on the CCD image with precision of approx. 1/10 of one pixel angular size. Every amateur thus can perform astrometric reduction up to a fraction of arc-second. Such precision was available only to few professional observatories a few decades ago.

- Images acquired with CCD camera are data files, which can be immediately processed using widely available personal computers. This is really very important advantage.
  - Astronomers appreciate their images are in the digital form from the moment of download from the camera to its final processing and archiving. Every image can be inspected just seconds after it is exposed. It is easy to make sure the observed object is in the center of the field of view, the telescope is properly focused etc.
  - Stacking of multiple exposures also increases dynamic range. Added resolution flux often exceeds detector dynamic range. Bright star can have hundreds of thousands or millions of ADUs, while the dim galaxy on the background only tens or hundreds of ADUs.
  - Digital image is immediately available for processing, be it photometry, astrometry etc. Digital images can be easily archived, copied, sent to colleagues, published on the web site etc.

Pixels and image scale

- Telescope angular resolution depends on the wavelength of the received light and on its aperture. Resolution increases when the wavelength decreases and aperture increases.
  - This is why the angular resolution of a small refractor with 5 cm aperture if around 1 000× better than the resolution of the radiotelescope with 100 m dish, receiving radio waves with 1 m wavelength (receiver diameter is 2 000× greater, but the wavelength is approx. 2 000 000× longer).
  - Visible light wavelength spans the range from 400 to 700 nm.
  - Telescope apertures varies and usually strongly depends on the budget available to every astronomer.

Telescope resolution

- But in reality the telescope resolution is limited by another phenomenon – turbulent air, also known as “seeing”. Warmer air has lower density than colder air and thank to lower density also lower refraction index. So the air turbulence deforms images of stars.
- Seeing is often expressed as minimal possible angular size (FWHM – Full Width Half Maximum) of a star.
- Typically the star image is distorted to a disk with 3” or 4”. If the angular size achieves 2” or less, seeing is very good. On the other side very bad seeing can blur the star image to 6” or 8”.

- If the seeing is taken into account, quality amateur telescope with 25 or 30 cm diameter achieves resolution equal to seeing limit, so increasing of the aperture does not bring better resolution, only allows shorter exposures.
  - This is of course valid for the middle-European weather. Locations chosen for greatest observatories (Mauna Kea, Chilean Andes, …) often offer seeing better than 1”.
- Every star on the CCD image should span at last 2 pixels in diameter.
  - Star image focused to single pixel limits the ability to precisely determine star position (it is not possible to calculate centroid) – image is under-sampled.
  - Star image covering too many pixels on the other side wastes light. The light from the star is divided into unnecessary small fractions – image is over-sampled.

Focal length for various pixel sizes

Pixel size	Focal length for 2”/px	Focal length for 1”/px
4,4 μm	45 cm	90 cm
5,4 μm	56 cm	112 cm
6,8 μm	70 cm	140 cm
7,4 μm	76 cm	152 cm
9 μm	93 cm	186 cm
13 μm	134 cm	268 cm
24 μm	247 cm	494 cm

- Over-sampling was a problem when CCD area was rather limited.
- CCD detectors with very large size are available now (now optics is the limit), so very high resolution and over-sampling (<1”/px) is used for aesthetic astrophotograpy.

Binning

- The term “binning” means adding of charge packets of individual pixels before they are digitized. Binning can be:
  - Vertical – more than single line is moved into horizontal readout register without reading (and thus clearing) of the horizontal register.
  - Horizontal – more than single pixel is moved from the horizontal register into the output node without resetting the output node (setting to reference voltage).
- Both binning methods can be combined (e.g. 2×2).
- Binning effectively increases the pixel size and limits the CCD resolution.

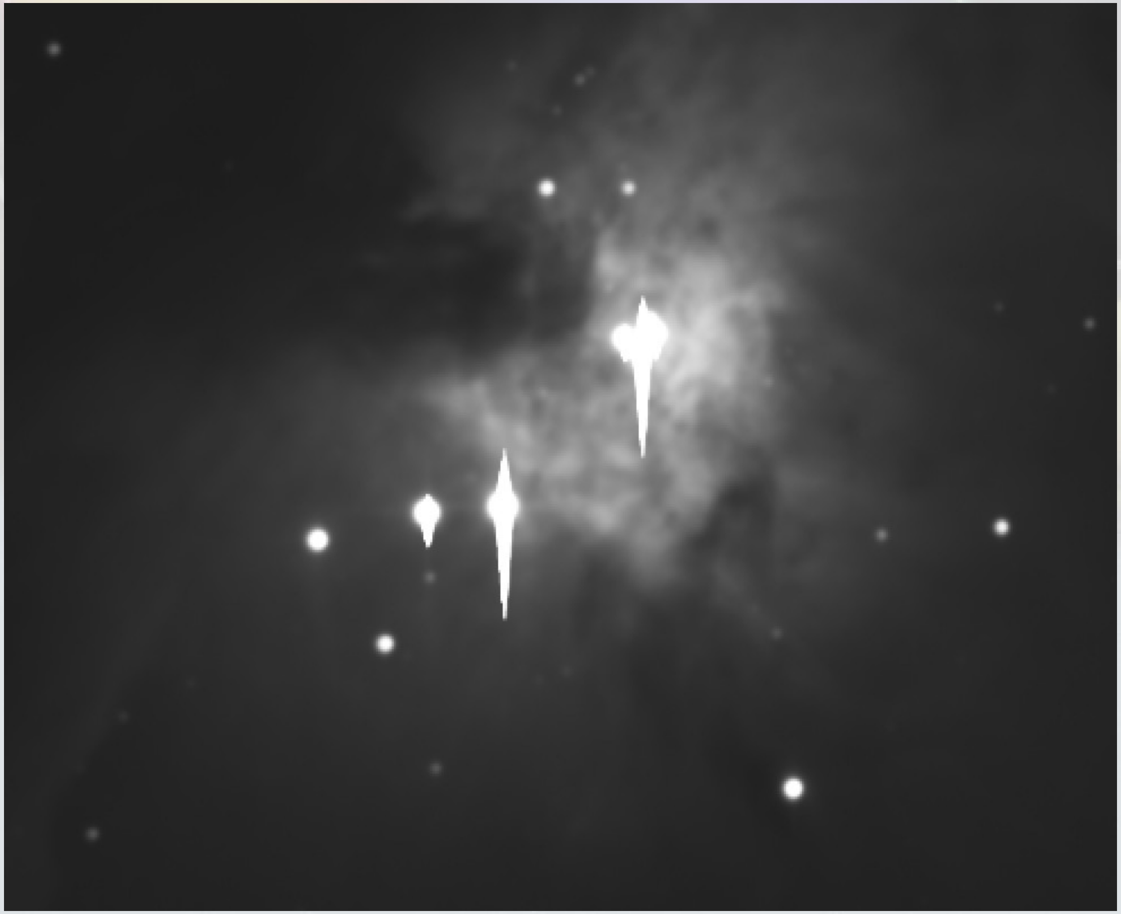
- Enlarging pixel through binnig does not bring S/N equal to a detector with appropriately greater pixels.
  - Smaller pixels, despite binned, still cover greater detector area with electrodes when compared with large pixels CCD.
  - Electronic binning introduces another noise into the signal.
- Binning increases demands to horizontal register pixels and the output node.
  - H-register and output node capacity is typically 2-time greater than the capacity of image pixels, so even 2×2 binnig can easily saturate and thus degrade signal.
- Binning can be implemented also by software.
  - If the image dynamic range is increased (e.g. from 16 to 32 bits/pixel), saturation never occurs.
  - Resulting S/N is even worse (pixels are independently digitized and e.g. sensor read noise affects all of them).

Binning and focal length

- If the focal length is too long relative to pixel size (e.g. pixel angular size is much lower than 1”), it is possible to use binning (pixel summing) to increase pixel size or focal reducer (optical element) to shorten the focal length.
- Usage of binning was somewhat undesirable when CCD sensors had just tens or hundreds thousands of pixels. Modern CCDs with millions of pixels can be binned without significant reduction of resolution. Multi-megapixel cameras with relatively small pixels are increasingly popular, despite pixel angular size is often lower than 1” when typical Schmidt-Cassegrain or Ritchey-Chretien telescope is used.

Blooming

- A bucket, into which more water is poured than is its volume, will overflow. Similarly, too big charge in a CCD pixel overflows (blooms) into surrounding pixels.



Anti-Blooming Gate (ABG)

- Special electrodes, intended for draining of the over-abundant charge before it starts to overflow into surrounding pixels, can be included into the CCD architecture.
  - All sensors, used in consumer electronics (still and video cameras, mobile phones, …), are equipped with ABG.
- Historically ABG introduced two principal problems, which caused refusing of ABG CCD by research community (and even today many scientists keep this attitude):
  - ABG lowered the QE by up to 50%.
  - ABG harmed linearity through full dynamic range, not only close so saturation. Photometry with ABG CCD was very inaccurate.

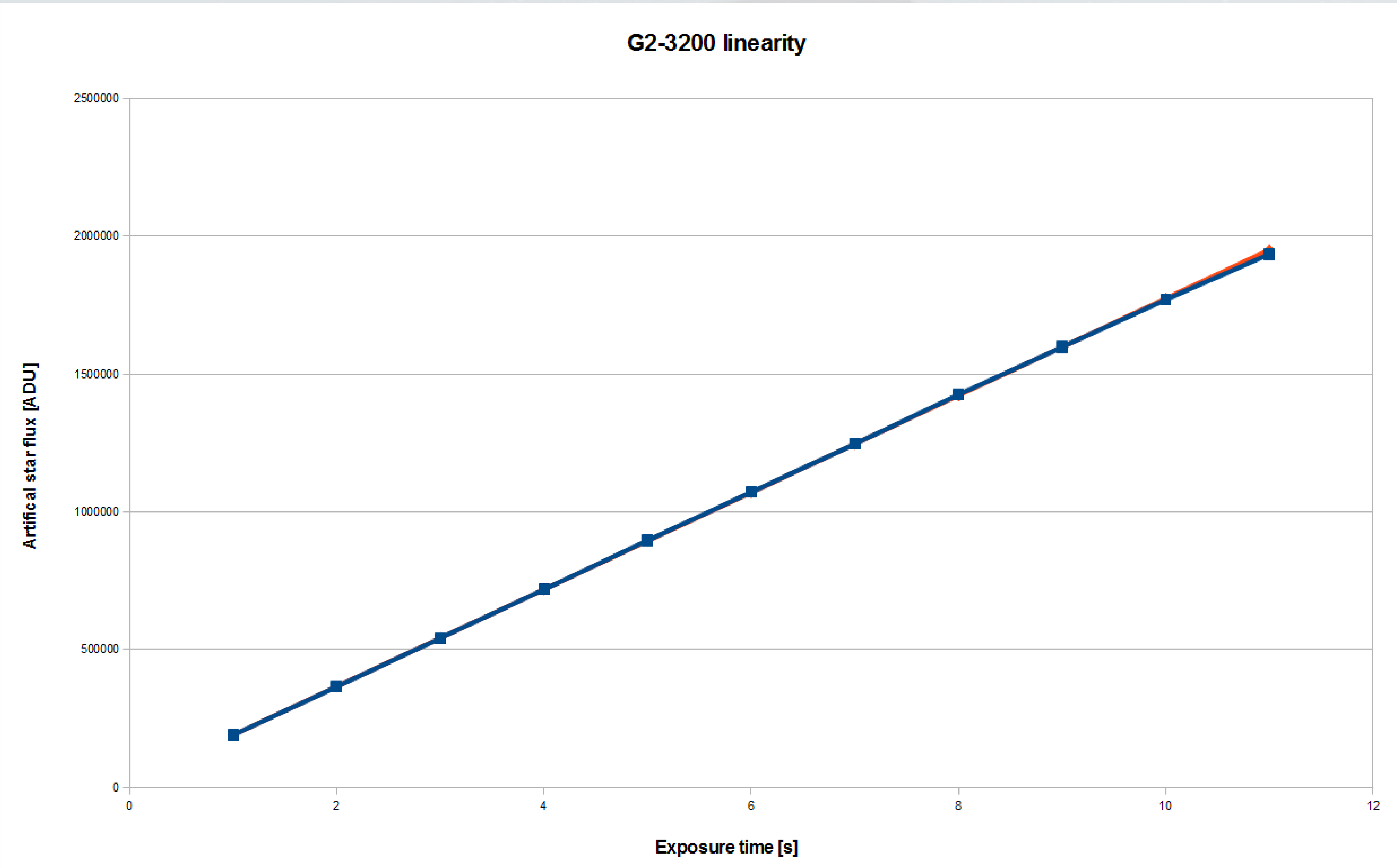
ABG on modern CCD

- Arguments against ABG CCD detectors are almost invalid these days.
  - There is an exception of really high-end, thinned detectors, using only the very fundamental CCD structure to achieve maximum possible QE and minimum read noise, for instance detectors of the E2V company.
- For instance CCD KAF-16803 with 9×9 μm pixels and ABG reaches maximum QE around 60%, while the non-ABG KAF-1603ME with the same pixels around 75% (which is not two times higher QE).
- With proper camera electronics design, keeping the saturation level well above the 65 535 ADUs, the ABG CCD linearity is better than 1%.

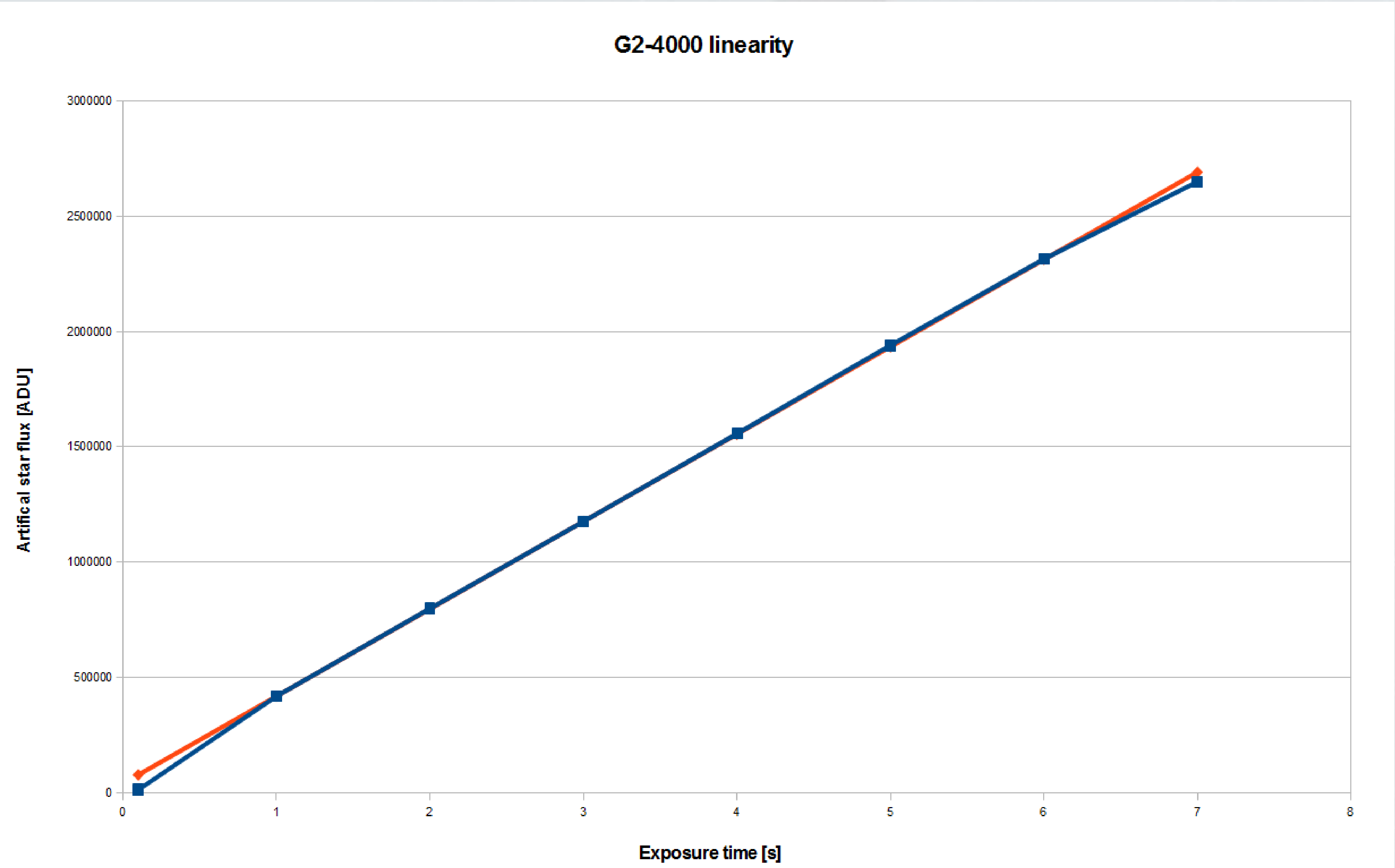
CCD linearity

- To achieve precise photometric measurements it is necessary to keep the relation between amount of incoming light and read signal as linear as possible.
  - Let's note the film emulsion, used before the CCD era also for photometric measurements, is strongly non-linear.
- The divergence of 1% through the camera dynamic range is considered sufficient.
- Modern CCDs are linear enough even if the ABG is present.
  - Also ABG has various intensity, from 100× in the case of KAF-16803, through 300× for KAI-4022 up to 1000× for KAF-8300.

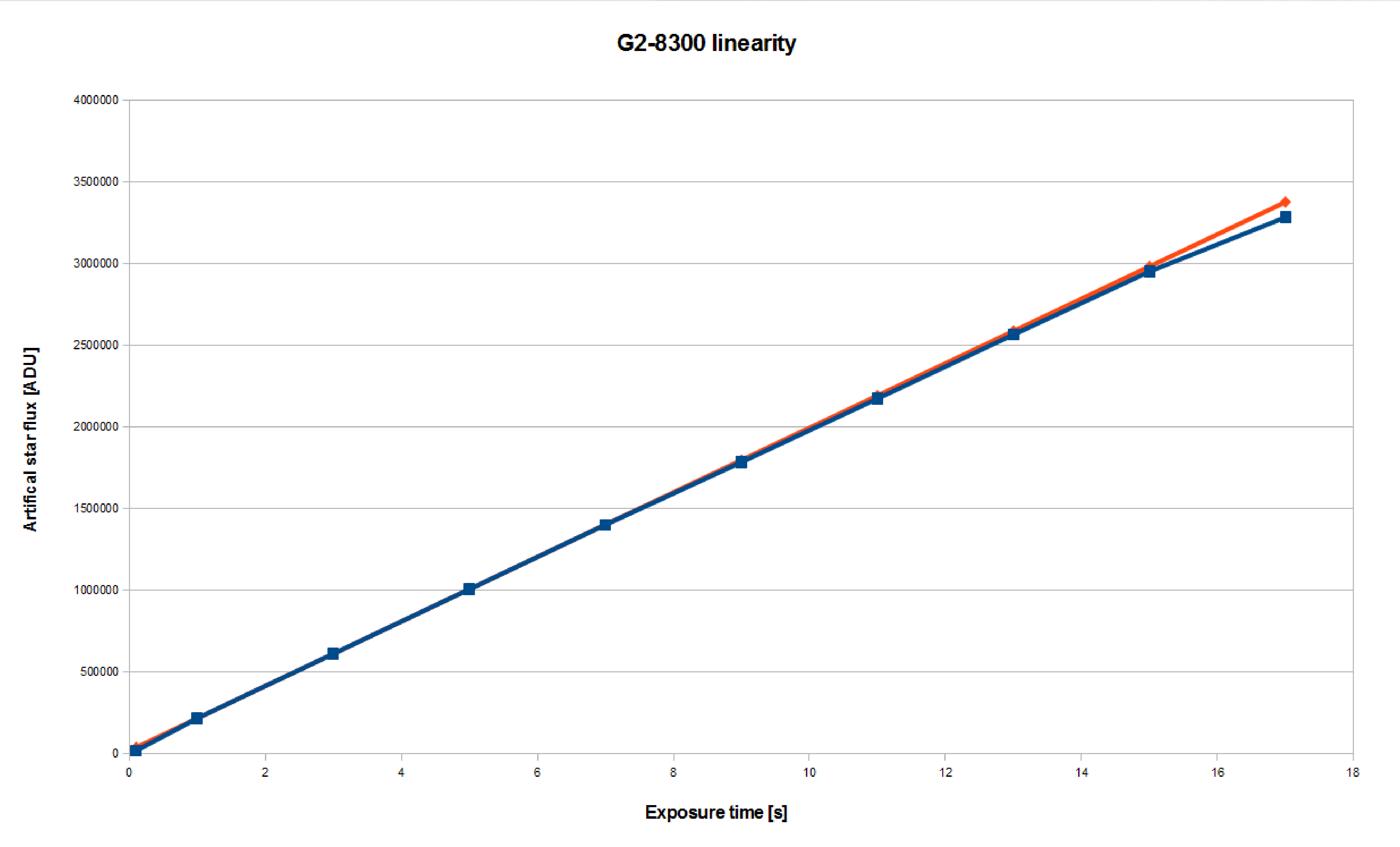
G2-3200 (NABG KAF-3200ME)



G2-4000 (ABG 300× KAI-4022)



G2-8300 (ABG 1000× KAF-8300)

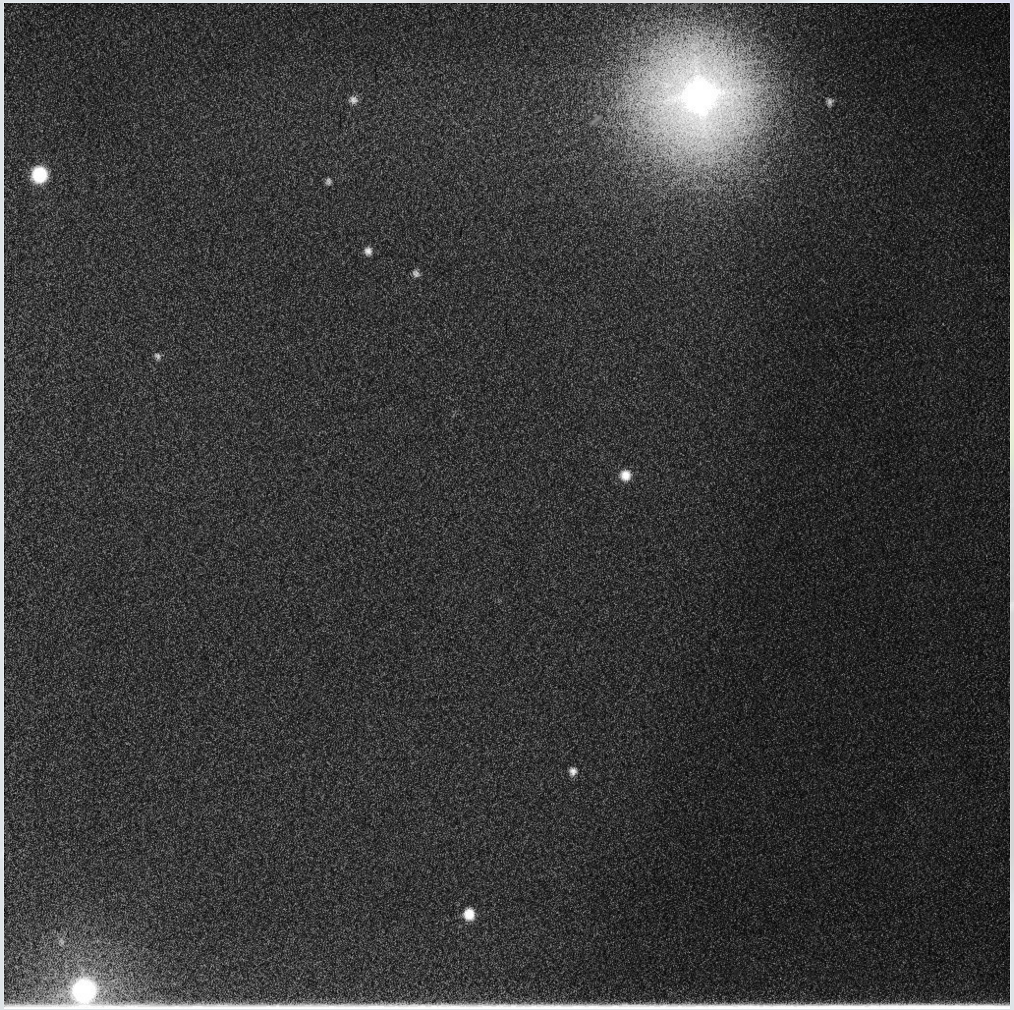


Astronomical image calibration

Raw image

- Image just read from a camera is called a “raw image”. It often looks quite ugly, especially when compared to fully processed images, which appear on web pages and magazines.
  - Image processing can remove dark and bright pixels, unwanted background gradients, reduce noise, sharpen subtle details, compress dynamic range etc.
  - Such image processing makes the image more pretty, but also alters information contained within the image. It can be performed only with images not intended for astrometry or photometry processing.

Raw images from world-class telescopes



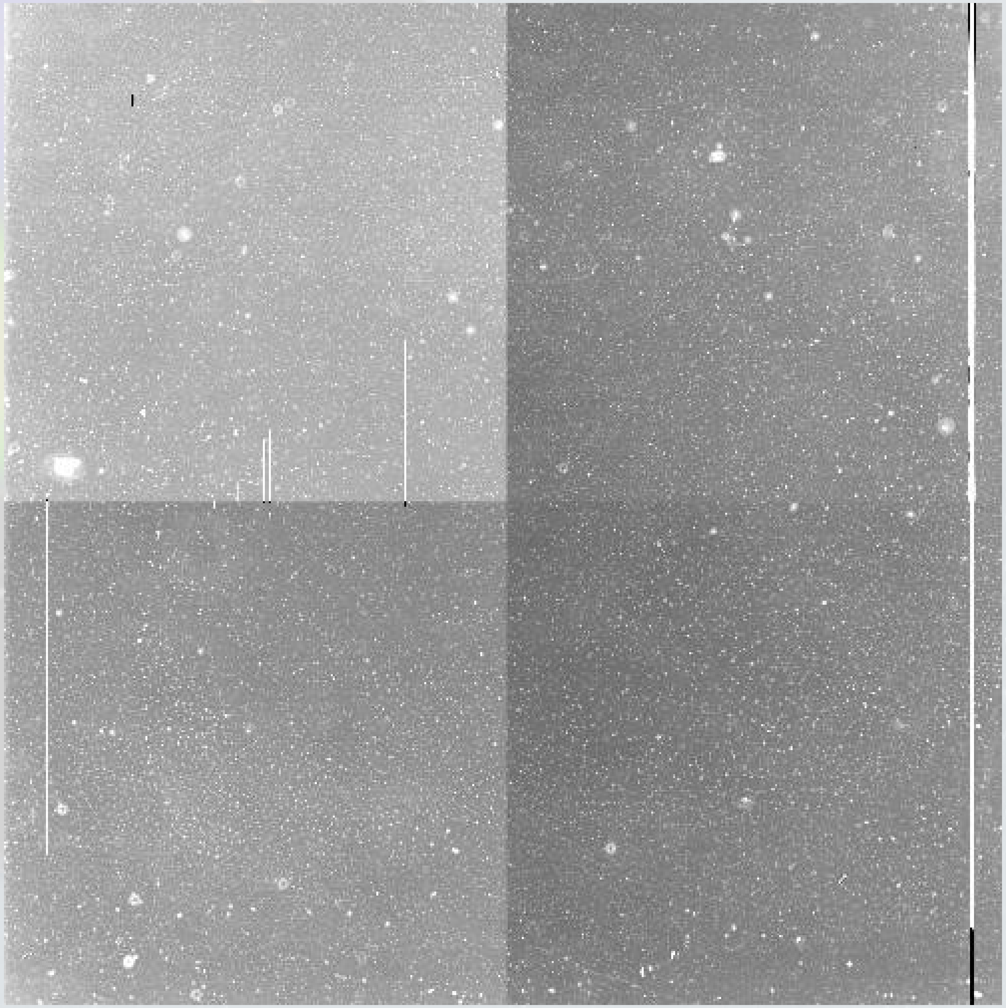
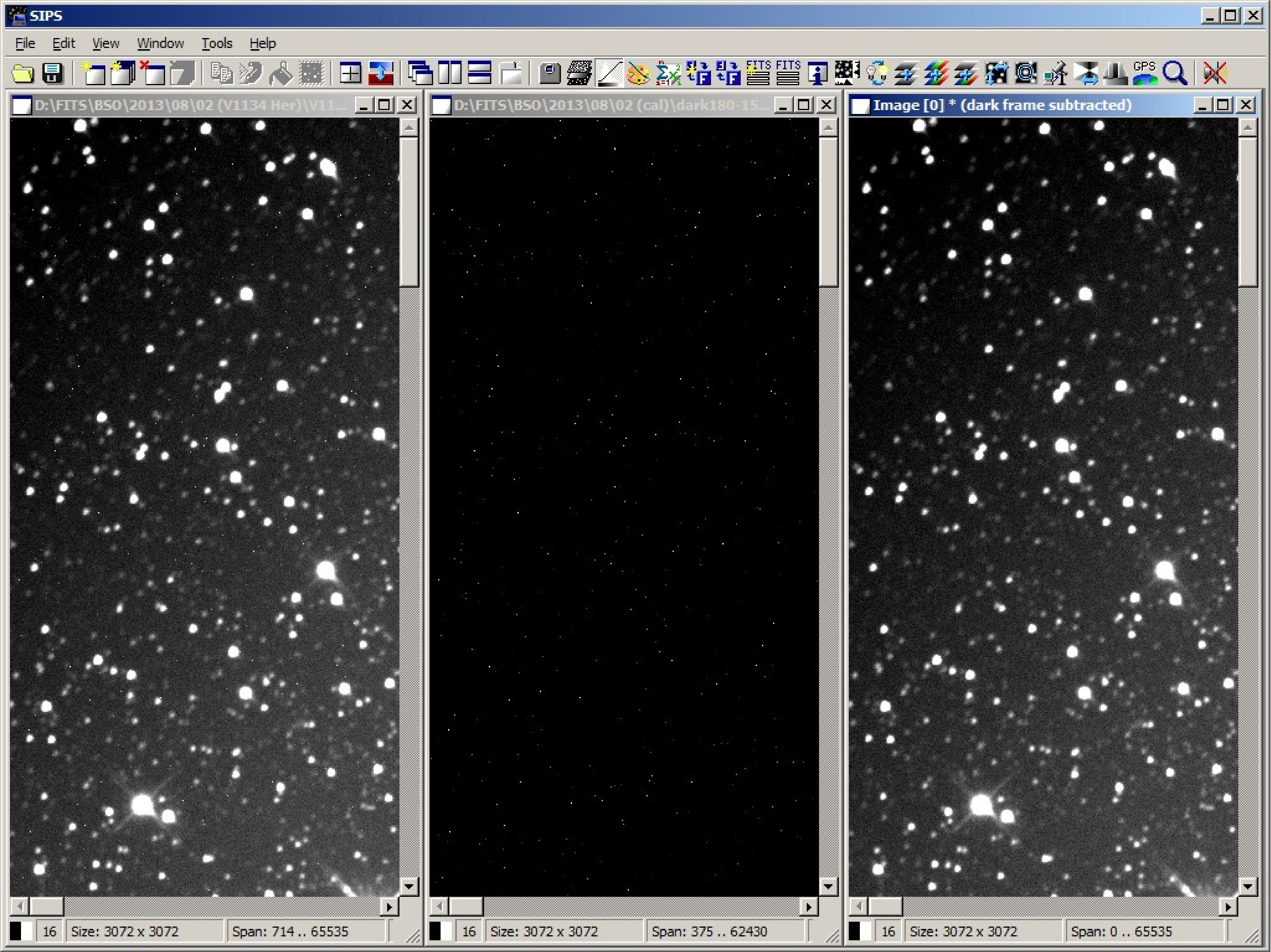


Image calibration

- Calibration of raw images typically increases their aesthetic appeal, but also increases the precision of astrometric and/or photometric measurements performed with these images.
    - In dependance on the CCD camera, telescope (or lens) and the target object the calibration can be simple or more complex. In some cases it could be even possible to skip calibration at all. But generally every CCD image should be calibrated.
- Calibration consists of two steps:
    1. subtraction of the dark-frame
    2. flat-field application

The dark-frame

- The idea behind the dark-frame subtraction is elimination (or at last reduction) of the dark current induced during the exposure.
- Dark current depends on the temperature. It doubles with approximately every 6 or 7 $^\circ$C.
  - For instance the OnSemi KAF-1603 doubles the dark current with every 6.3 $^\circ$C.
- The charge, accumulated in pixels, is also proportionally dependent on a exposure time (dark current is expressed in electrons per pixel per second at given temperature).
- To reduce dark current, dark-frame must be acquired for the same time at the same temperature like light image.



SIPS
File
Edit
View
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Tools
Help
FITS
FITS
GPS
D:\FITS\BSO\2013\08\02 (V1134 Her)\V11...
D:\FITS\BSO\2013\08\02 (cal)\dark180-15...
Image [0] * (dark frame subtracted)
16
Size: 3072 x 3072
Span: 714 .. 65535
16
Size: 3072 x 3072
Span: 375 .. 62430
16
Size: 3072 x 3072
Span: 0 .. 65535

Calibration image acquisition

- The dark current of the majority of CCD pixels is typically very close to the value stated by the manufacturer, but a small amount of pixels often exhibit much higher dark current (up to several orders of magnitude). These pixels are called “hot pixels” and are visible as bright points.
- Because the signal deviation corresponds to √ of the signal level, hot pixels have very high deviations.
- This is why the calibration quality increases when the calibration image is created as combination of multiple individual frames.
  - Empiric rule says, that total exposure time of calibration images should be at last 5-times the exposure time of light images.

Calibration image acquisition (2)

- Calibration images can be combined into resulting "master" image in two ways:
  - Mean (average) of individual frames – the minus side of mean is that possible extreme pixels (e,g, particle traces) affect the resulting image.
  - Median of individual frames – eliminates extremes and choses the value in the middle.
- Median cannot be created if the image mean value differs (which can be a case of e.g. flat files taken on the sky).
  - In such case mean values of individual frames must be equalized.
  - Equalization of the mean value can be additive or multiplicative.

“Flat field”

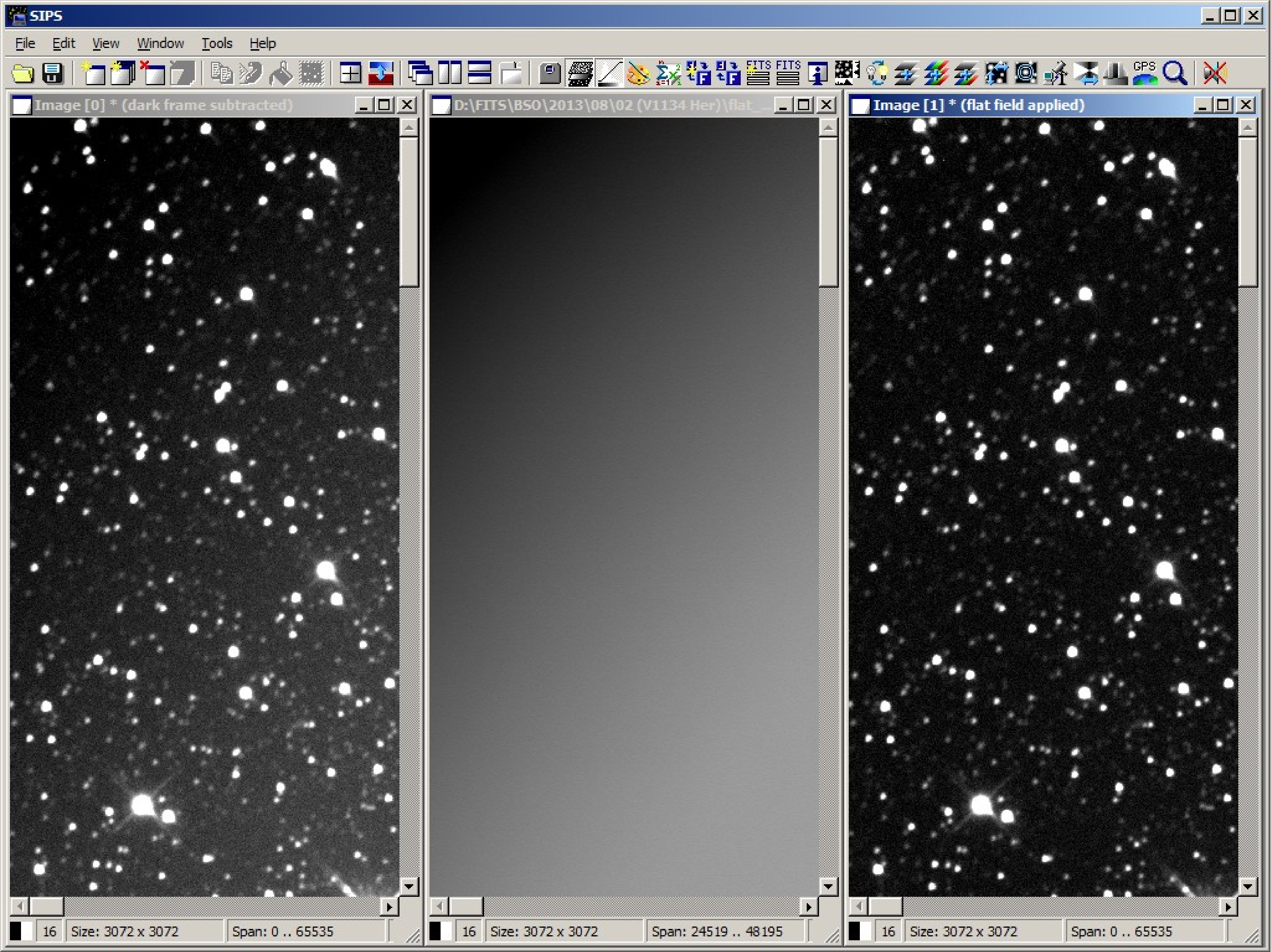
- The field of view is often illuminated irregularly by the telescope (or lens) – the illumination intensity on the edges is typically lower compared to field of view center.
- Dust particles on the filters, CCD chamber optical window and on the CCD cover glass cast ring-like shadows. All these effects change intensity of the detector illumination and cause not only aesthetic defects, but also reduce the measurement precision.
- The influence of the above effects can be eliminated (or at last reduced) by a flat-field application.

Flat-field application

- Flat-field is an image of evenly illuminated flat surface. All variations of image brightness are caused by the optical system only.
  - ADU values of the ideal flat-field frame are around a half of the camera dynamic range, which means around 33 000 ADU in the case of 16-bit camera electronics.
- There are several ways how to obtain flat-field:
  - By imaging of the close, evenly illuminated flat surface. But it could be difficult to illuminate a flat surface really evenly. Also the geometric proximity of the surface can cause differences in the field illumination.
  - By imaging of the sky during dusk or dawn. Processing is more difficult due to changes of brightness during exposures, but the sky is more uniform compared to artificially illuminated surface.

Flat-field application (2)

- Flat-field application means dividing of every pixel of raw image by the corresponding pixel of the flat-field frame.
  - Pixels brighter due to irregular illumination are divided by pixel value of the flat-field, which is brighter from the same reasons, and vice versa.
- Division degrades the range of pixel values, which is why every pixel is multiplied by the flat-field mean value at the same time.
  - If the calculation is performed with the integer numbers, the multiplication must be of course performed before the division, else the precision lost during integer division would completely harm the image.


SIPS
File Edit View Window Tools Help
Image [0] * (dark frame subtracted)
D:\FITS\BSO\2013\08\02 (V1134 Her)\flat_...
Image [1] * (flat field applied)
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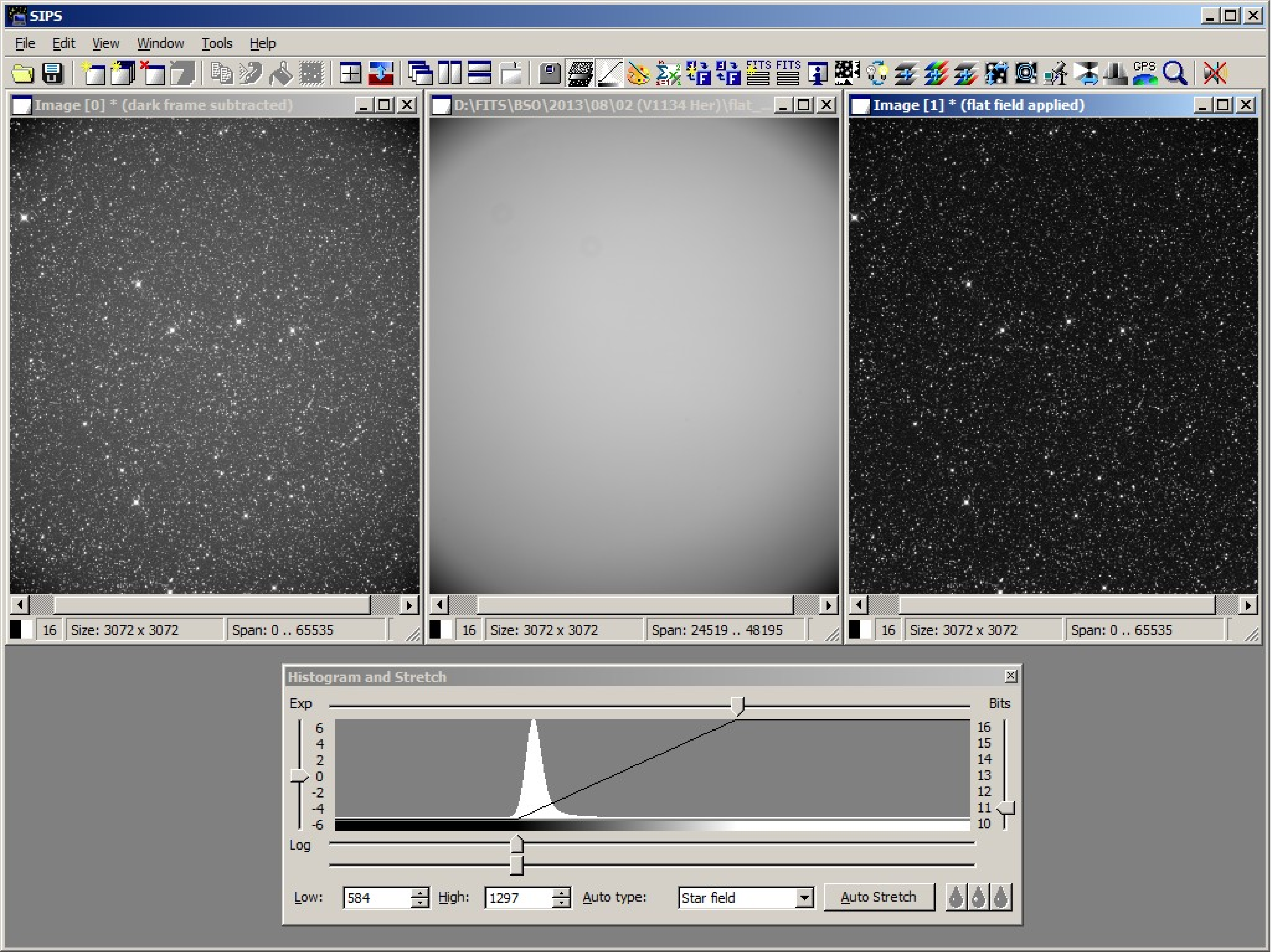
16 Size: 3072 x 3072 Span: 24519 .. 48195
16 Size: 3072 x 3072 Span: 0 .. 65535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File Edit View Window Tools Help
Image [0] * (dark frame subtracted)
D:\FITS\BSO\2013\08\02 (V1134 Her)\flat_...
Image [1] * (flat field applied)
16 Size: 3072 x 3072 Span: 0 .. 65535
16 Size: 3072 x 3072 Span: 24519 .. 48195
16 Size: 3072 x 3072 Span: 0 .. 65535
Histogram and Stretch
Exp
Bits
6 4 2 0 -2 -4 -6
16 15 14 13 12 11 10
Log
Low: 584 High: 1297 Auto type: Star field Auto Stretch

- Sources of information:

  - Kodak CCD Primer (#KCP-001), parts 1 and 2
  - Solid State Image Sensors Terminology, Kodak Application Note (DS 00-001)
  - CCD Image Sensor Noise Sources, Kodak Application Note (MTD/PS-0233)
  - J.B.Pawley, Handbook of Biological Confocal Microscopy, Springer (ISBN: 978-0-387-25921-2)
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  - http://www.nobelprize.org/nobel_prizes/physics/laureates/2009/smith-photo.html
  - http://www.astro.caltech.edu/palomar/
  - http://www.astro.uni-bonn.de/
  - http://www.gxccd.com/

- Authors of used astronomical images:
  - Didier Chaplain and Laurent Bourgon (North America and Pelican nebulae)
  - Martin Myslivec (the Sun in the Hα line)
  - Pavel Cagas

Thank you for you attention.

Questions?