Observational Astrophysics
18. Optical Detectors

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1 Introduction

Up to now, we have discussed electromagnetic radiation, the effects of the atmosphere, the parts of optical and infrared (IR) telescopes, and instruments for photometric and spectroscopic measurements. We have even glanced over many different types of measurements we might be interested on (positions, sizes, motions, etc). To perform those measurements we have to first detect the incoming light and make some kind of record of that detection. That is the role of the detector. The modern preference is, of course, on producing a record that can be analyzed by a computer.

Detectors are positioned at the focal plane of the instrument, the place where the image is formed. For the case of IR, we already had a look at some properties of detectors. Here, we will look at detectors from a more general point of view but also on more specific details of charge-coupled devices (CCD), which is the most common choice of optical detector. Nevertheless, the text recommended below covers different types of detectors over a wide wavelength range.

Understanding the detectors that you need to use for your observations is key to properly carrying out the measurements and performing the data processing needed to interpret those measurements.

2 Read this text

On the topic of detectors, I recommend reading Chapter 7 of the book "Observational Astrophysics" (Léna et al. 2012)[1]. Note however, that this chapter contains more than 120 pages. This is because the chapter provides a wide view of astronomical detectors, not only regarding electromagnetic radiation from gamma-rays to radio, but also a discussion on detecting neutrinos and gravitational waves. Since our lectures are focused on optical and infrared wavelengths, please read at least Sections 7.1, 7.2, and 7.3, which discuss general concepts regarding the detection of electromagnetic radiation and then Subsections from 7.4.5 to 7.4.10, which discuss detectors used in the optical and infrared. The remaining Sections of the Chapter can be read if you have an interest in the other wavelength windows or in neutrinos and gravitational waves. Note, however, that this text might not be the most updated source.

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[1] `https://link.springer.com/book/10.1007/978-3-642-21815-6`

3 Summary of concepts

- When discussing detectors we will repeatedly mention exposure, which means a measurement connected to the total amount of energy falling on a unit area of the detector. Something related to the irradiance (W m^{-2}) times the exposure time.
- Quantum efficiency (QE) of a detector is the ratio between the number of detected photons and the number of incident photons.
- Dark current or dark noise is the signal outputted by the detectors even when it is not illuminated. In CCDs, for example, it is usually given in units of electrons per pixel per hour.
- The dynamic range is the interval between a sensitivity threshold (e.g. the dark signal) and the saturation level (the maximum signal, also called full well capacity). Sometimes this will be defined only within the region where the response is linear.
- The interaction of light with matter can be either coherent or incoherent, depending on whether the detection is phase-sensitive or is based on the energy of the photons only.
- Some detectors can only measure signal from a single point of the image formed at the focal plane (thus they are called single-channel detectors). Some detectors can be made into arrays of "independent single detectors" (or pixels) which can then, instead of a single point, cover a two-dimensional area in focal plane (they are called multichannel detectors). Sometimes these pixels can not really be made to be closely packed together, and the detector is said to have a low "geometrical filling factor". Ideally, we would like large multichannel detectors with high filling factors (i.e. with no important gaps between pixels).
- One way to classify detectors is to divide them in these three broad groups:
  1. Photon detectors: where photons release electrons when interacting with the material. This type of detector is widely used in wavelengths ranging from gamma rays to the far infrared.
  2. Thermal detectors: where the photon energy is used to heat up the material, changing some of its properties (e.g. resistance, voltage, etc). This type of detector is mostly used for observations in wavelengths from the infrared to sub-millimeter. They have broad spectral response, what also makes them useful for measuring the total solar irradiance from space.
  3. Coherent detectors: where the electric field of the wave is sensed directly and in this way the phase information is also recorded. This type of detector is mostly used for observations from the far infrared to the radio, and we will not cover them here.
- Photon detectors can be further divided into:
  1. Photoemission: making use of the "external photoelectric effect", where the electron is completely removed from the material.
  2. Photoabsorption: making use of the "internal photoelectric effect", where the free electron remains inside the volume of the material.
- The response of a thermal detector depends only on the total power absorbed and and is independent of wavelength.

- A photon detector is sensitive to the rate of arrival of photons and the response is dependent on wavelength. There is some maximum, cut-off, wavelength where the photon energy is no longer able to produce a photoelectric event.

- Photographic plates (or similar) were the first type of detector (other than the eye) used in astronomy, starting on the 1850s (see Hoffleit 1950, for an early history)[2]. This is a detector of the photoabsorption type. They allowed long exposures that could reveal faint objects. They were widely used in the optical until the 1980s, when charge-coupled devices (CCDs) became the detector of choice. Many important and still used surveys were made with photographic images (many now digitized), e.g. the Hubble Guide Star Catalog and the Palomar Observatory Sky Surveys (POSS I and POSS II).

- The basic concept of a photographic plate uses a salt compound of silver (like silver bromide, AgBr) supported by a solid, transparent medium, usually made of gelatin. When light is absorbed by the salt crystals, free neutral silver is created causing blackening of the material. The density of the silver is what measures how exposed (blackened) a certain region of the plate was. Advantages include their large size (with a large number of pixels), the cheap price, easy of storage, and sensitivity to a wide range of wavelengths. However, the processing of a photograph is a complex procedure, its quantum efficiency is low ($\sim$4%), and its response to light is non-linear at low light levels. Furthermore, the response curve is not exactly very stable and can differ even between photographic emulsions of the same type.

- Electronic forms of recording images have several advantages: the signal can be easily transmitted to a computer that can be located remotely, quantum efficiency is much higher than that of photographic plates, and response is more linear. Nevertheless, the operation can be complex and the costs are higher.

- The photomultiplier tube is a photoemission type of detector which was once widely used for optical photometry. It is still used for detection of Cherenkov radiation created by neutrino and cosmic rays, or in applications where very rapid responses are required. Such detectors are a tube containing a series of electrodes. The first is the one exposed to the radiation. The electron is emitted from the photocathode surface and subsequently amplified (multiplied) by a cascade of impacts on secondary electrodes, before the signal is detected as a pulse.

- Semiconductor devices are photoabsorption detectors and they work based on essentially two types of interactions: the photoconduction effect and the the photovoltaic (or photodiode) effect. See the notes on Infrared Astronomy for more details on photoconductors and photodiodes, not repeated here.

- When atoms join to form solid crystals, the electrons in the outer orbits interact to bind the atoms together. These outer (or valence) electrons are shared among the atoms. The energy levels split, essentially forming a continuous band known as the "valence band". The unoccupied higher energy levels also form bands that are called "conduction bands". The energy region between the valence and conduction bands is the "energy gap". In metals, the valence and conduction bands overlap so that the electrons are free to move and conduct electricity. In insulating materials, the energy gap is very wide, the conduction band is empty, and there are no electrons to conduct electricity. Semiconductors have the interesting property where valence electrons can absorb energy and be promoted to the conduction band, where they can then conduct electricity (under the influence of an electric field).

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[2] `https://babel.hathitrust.org/cgi/pt?id=mdp.39015011394940&view=1up&seq=11`

- Detectors based on photoconduction are made of one type of semiconductor material. Its conductance is changed by the creation of free charges when photons are absorbed. An external electric field is usually applied on the material to move the charges.

- In photodiodes, an internal electric field is created by the junctions between materials that have different electrical properties. Free charges generated in the junction react to the internal field moving before recombination can occur.

- The CCD was invented in the end of 1969 by Willard Boyle (Canadian physicist) and George Smith (American physicist) working at the Bell Telephone Laboratories in the USA (Boyle & Smith 1970)[3]. They were jointly awarded half of the Nobel prize of Physics in 2009 for this discovery.

- CCDs became widely used because they can integrate over long time intervals, their dynamic range is high, the quantum efficiency is high (nowadays it can reach $>$ 80-90% in a wide wavelength range, but is lower in the blue, $\lesssim 50\%$, because silicon absorbs such photons), and they are easily made into arrays that can be used for imaging areas of the sky, instead of single points.

- Each pixel of a CCD works as a Metal-Oxide-Semiconductor (MOS) capacitor. The semiconductor material (silicon) is covered with an insulating layer (such as silicon oxide, SiO). A metal electrode is positioned above this arrangement and a voltage is applied. When a photon passes through the insulator and is absorbed by the silicon, an electron-hole pair is created. The voltage moves the electron towards the insulator, where it stops. As the electron moved away from the hole, they can not recombine. The same happens with the next photons, and the charge is accumulated close to the insulator (so the structure behaves as a capacitor). The positive voltage on the electrode also has the effect of repelling the holes, creating a "depletion region" where the electrons can safely accumulate. The CCD is an array or grid of such elements.

- The voltage applied with the electrode can of course be controlled. This can be used to increase and decrease the depletion region. Thus, the charge storage capacity can also be controlled.

- Besides electron-hole pairs created by incident photons, thermally excited charges can also appear in the material. It is to reduce the number of such charges, and reduce the background signal that they produce (i.e., the dark signal), that CCDs need to be cooled down (to a temperature of between 77-220 K using liquid nitrogen).

- After integration is complete, the accumulated charges need to be read out. In CCDs, this is done through "charge coupling". In a three-phased CCD, each pixel actually has three electrodes, not one. During exposure, the central electrode has a higher voltage than the ones at the edges. The charges then accumulate in the depletion region of this central electrode. Columns in the CCD are separated by insulating material, but not the rows. What separate the pixels in the row direction are the electrodes with low voltage. For the read out, the voltage on the electrodes is cycled in one direction, i.e. the voltage of the central electrode will be decreased and the voltage in one of the electrodes at the edges will be increased (the one in the direction to where the charges should be moved). The charges then move towards

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[3] See the paper here

the next electrode. With three voltage cycles, the charges from one row are moved to the next. This process of raising and lowering the voltage is known as clocking.

- In this process, the last row was moved to a region of the CCD called the “output register”. In this region, the electrodes are arranged in the orthogonal direction and in it the charge transfer will happen in the column direction. As the output register is a single row, it is also called the serial register. The main area of the CCD is also called the parallel register. At the end of the output register there is a single output amplifier which is where the charge is detected, measured, and recorded (one pixel at a time).

- This whole process has to be repeated until all rows are given to the output register and the charge in all pixels are measured and recorded. The efficiency of the charge transfer is very high, >99.999%. For large CCDs, the read out can take 30-60s.

- One solution to speed up the read out is the “frame transfer CCD”. Essentially, a large CCD is divided into two areas of same size, where one is used for the exposure and the other is hidden under a protective mask. After exposure is completed, the charges are quickly transferred to the hidden area. And only from this hidden area, at a slower pace, the charges will be transferred to the output register. In the mean time, another exposure can start using the illuminated area of the CCD. Another solution is to divide the CCD in regions that can be read out independently by placing (2-4) output amplifiers in different corners of the detector.

- The electrodes on top of the CCD actually absorb some of the radiation, particularly in the blue wavelengths, causing a decrease in the quantum efficiency. To overcome that, CCDs can be turned around and illuminated from the back (“back illuminated CCDs”) so that radiation directly interacts with the silicon layer.

- CCDs used to be relatively thick ($\sim 300\mu$m) while the depletion region under the electrode had $\sim$10μm. The problem then was that the region the electrons had to travel was too large. So the CCDs also have to be thinned to $\sim 15\mu$m or so. Thinned, backside-illuminated CCDs have excellent sensitivity in the blue. However, if thinned too much they will lose sensitivity in the red. The red photons need a thicker region to interact with the silicon, otherwise they will just pass through it.

- Thinned CCDs are more mechanically fragile and can bend. They are also prone to fringing in red wavelengths, caused by interference of light suffering multiple reflections on the top and bottom of the structure.

- When the accumulation of electrons approaches its maximum (the saturation level), mutual repulsion can make some electrons to move to nearby pixels (called blooming or charge bleeding). When observing bright objects, this can pixels in the same column which are not insulated from each other. Some CCDs have extra circuits (anti-blooming) for these charges to leak out without contaminating nearby pixels.

- Besides the dark thermal noise mentioned above, additional noise is introduced during transfer and amplification of the signal, the so-called readout noise. The readout noise, with rms typically between 2-5 electrons depends on the speed of the readout, with faster readout rates increasing the noise (early CCDs had readout noises that were 100 times or more larger than the ones of today).

- The text recommended for reading above mentions CCDs with 2048 x 4096 pixels format. Nowadays, CCDs with 9216 x 9232 pixels can be produced[4].

- Larger areas can also be obtained by creating mosaics of many CCDs, as we have seen in some of the instruments we discussed before. Construction of mosaics is not completely trivial. Some effort has to be put into closely packaging of the CCDs together with all the electronics needed for their control and read out. The camera design has to be taken into account. Gaps will be present in the area coverage and wide-field imagers can suffer from curvature of their focal plane.

- One recent innovation that can help to deal with focal plane curvature is the manufacturing of curved CCDs (Swain et al. 2004)[5]. BlueMUSE, a new integral field spectrograph proposed for the VLT, is actually considering a design that benefits from the use of curved CCDs (Jeanneau et al. 2020)[6].

- The gain of a CCD is the conversion made by the output electronics between the number of electrons and the unit that is registered (the ADU, Analog-to-Digital Unit). This is set by the number of bits in the A/D converter. Let's say a CCD has full well capacity of 90000 electrons and we are using a 16-bit A/D converter (values up to 65535 can be stored). The optimal gain, that can represent the full well capacity in ADUs is given by $90000/65535 \sim 1.37$ or 1.4 electrons/ADU.

- When using some instruments, you might be allowed to choose between "high-gain" and "low-gain" settings of the CCD. High gain is generally used when observing faint objects, where the signal is far from saturation. When the electrons are converted to ADU, the number is rounded to an integer. This can introduce something called "digitization noise". The high gain setting produces more ADUs for the same number of electrons, decreasing the effect of the rounding. And if your object is bright, you would prefer to use low gain, to be able to convert more electrons into ADUs.

- CCDs usually also allow a processing called "on-chip binning". This option allows the combining of charges accumulated in rectangular groups of neighbouring pixels. The effect is that of creating a larger pixel sometimes called "superpixel". On-chipping binning reduces the spatial resolution of the image (or if applied in the dispersion direction of a spectrum, might result in decreased spectral resolution). The advantage is in increasing the signal-to-noise without before adding the readout noise. Binning can also be done after readout, during the imaging processing. In this case, however, readout noise will already have affected the signal of each original pixel.

- The read out process described above takes place at the surface of the silicon semiconductor. CCDs that operate like this are called "surface-channel" CCDs. Turns out this is far from optimal. The surface layer and the edges of the electrodes can have irregularities and defects which result in trapping of charges. This effect can be quite important when observing faint objects that generate only few electrons. The solution is to have a positively charged layer of n-type silicon between the insulating material and the p-type silicon. This arrangement "buries" the depletion region deeper in the CCD and away from the surface. CCDs that operate like this are called "buried-channel" CCDs. This arrangement reduced the number of

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[4] https://www.teledyne-e2v.com/markets/space/astronomy-imaging/ccd290-99/

[5] https://ui.adsabs.harvard.edu/abs/2004SPIE.5301..109S/abstract

[6] https://ui.adsabs.harvard.edu/abs/2020SPIE11447E..5MJ/abstract

possible regions that can trap charges and improves the transfer efficiency. However, it also decreases the size of the depletion region, so the total charge storage capacity of each pixel is smaller. Modern scientific CCDs are of the buried-channel type.

- Electron-Multiplying (EM) CCDs have one difference with respect to normal CCDs. Something called as "multiplication output register", with several elements, is now placed between the serial output register and the output amplifier. Inside each element, there is a small chance (1-1.5%) of an avalanche multiplication that transforms one electron into two. After the electrons move through the complete multiplication register, a gain of about 1000 has been obtained in the signal. The noise introduced by the output amplifier is then, in comparison to the signal, much less important. See Mackay et al. (2012)[7] for a discussion.
- Although CCDs are sensitive to UV light (even down to low energy X-rays), they are usually less efficient because the structure around can also absorb UV photons. A preferred solution seems to be the use of a photoemission device like a photomultiplier tube (PMT). Several substances sensitive to UV light are available and can be used. However, the PMT is a single channel detector. One alternative is the creation of a microchannel plates (MCP). These are slabs of glass with several parallel microscopic pores that are coated substances that emit secondary electrons. Each pore (channel) works as a PMT and produces a cascade of electrons. An array of anodes is used to collect the emerging electrons from the plate. Such devices are called Multi-Anode Micro-channel Arrays (MAMA) detectors. The Space Telescope Imaging Spectrograph (STIS) uses two MAMA detectors to cover the far-ultraviolet (115-170 nm) and the near-ultraviolet (16-310 nm) regions, see Timothy (2016)[8].
- Complementary Metal Oxide Semiconductor (CMOS) arrays are now widely used in commercial applications but not so much in astronomical applications yet. In CMOS detectors, each pixel comes with its own circuitry for readout and amplification. This can take some space and reduces the filling factor of the detector. For more details (although its a relatively old reference already), see Hoffman et al. (2005)[9].

4 Additional reading

If you would like to read more details about photographic plates, see Chapter 2 of the 4th edition of "Astrophysical Techniques" (Kitchin 2020)[10].

For additional details on CCDs, beyond what was summarized here, see Chapters 7 and 8 of the book "Electronic Imaging in Astronomy" (McLean 2008)[11]. For additional information, see the "Handbook of CCD astronomy" by Howell (2006)[12].

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[7] `https://ui.adsabs.harvard.edu/abs/2012SPIE.8453E..02M/abstract`

[8] `https://ui.adsabs.harvard.edu/abs/2016JATIS...2c0901T/abstract`

[9] `https://ui.adsabs.harvard.edu/abs/2005ExA....19..111H/abstract`

[10] It seems that more recent editions do not cover this material anymore. At least the 4th edition still had a Section 2.2 with more than 15 pages dedicated to details of photographic plates, emulsions, processing, etc. Search for "astrophysical techniques kitchin" in Google Scholar.

[11] `https://link.springer.com/book/10.1007%2F978-3-540-76583-7`

[12] `https://www.researchgate.net/publication/332392902_Handbook_of_CCD_Astronomy`

References

Boyle, W. S. & Smith, G. E. 1970, Bell System Technical Journal, 49, 587

Hoffleit, D. 1950, Some firsts in astronomical photography (Harvard College Observatory)

Hoffman, A., Loose, M., & Suntharalingam, V. 2005, Experimental Astronomy, 19, 111

Howell, S. B. 2006, Handbook of CCD astronomy, Vol. 5 (Cambridge University Press)

Jeanneau, A., Kosmalski, J., Muslimov, E., et al. 2020, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 11447, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 114475M

Kitchin, C. R. 2020, Astrophysical techniques (CRC press)

Léna, P., Rouan, D., Lebrun, F., Mignard, F., & Pelat, D. 2012, Observational astrophysics (Springer Science & Business Media)

Mackay, C., Weller, K., & Suess, F. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8453, High Energy, Optical, and Infrared Detectors for Astronomy V, ed. A. D. Holland & J. W. Beletic, 845302

McLean, I. S. 2008, Electronic Imaging in Astronomy

Swain, P. K., Channin, D. J., Taylor, G. C., Lipp, S. A., & Mark, D. S. 2004, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 5301, Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications V, ed. M. M. Blouke, N. Sampat, & R. J. Motta, 109–129

Timothy, J. G. 2016, Journal of Astronomical Telescopes, Instruments, and Systems, 2, 030901