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CHAPTER TWO

A Digital Image – The Basics

Well, what is a digital image? Perhaps it is easiest to start with one of the most familiar types of image we encounter. A printed photograph – whether the picture originates from a digital or film-based camera – will consist of a rectangular area covered with tiny dots of varying intensity and color. When viewed from a distance the dots merge and the print shows how the photographed scene would have appeared had you been there to see it. The fact that a photograph is made up of dots – known as pixels – is not normally apparent unless you try to enlarge it too much or use a magnifying glass.

The crystals that make up a film emulsion-based photograph – in effect defining the pixels – are packed together closely, but are randomly located within each frame, whereas digital images employ a grid-like layout made up of small rectangular (or square) light-sensitive pixels. The variation in brightness or intensity of these pixels represents a two-dimensional (2D) view of the world – or, in the case of astronomy, space. Unsurprisingly, digital images are like this because most cameras employ sensors that consist of a flat rectangular patch of silicon that has been divided up into a grid of minute light-sensitive rectangles.

The sensors have electronics associated with them that can quickly determine how much light has impacted onto each of the light-sensitive pixels during the exposure. These sensors are placed at the focal plane – i.e. the point where the light comes to a focus – of a camera lens or telescope and, as a result, a digital image is generated by determining a numeric value indicating how much light fell onto each pixel of the image. The numeric value for a given pixel will not be the same as the number of photons collected but will certainly be closely related and broadly proportional to it. Creating this gridded list of numbers is quite an undertaking, given that quite inexpensive digital cameras can now boast 6 million pixels, while professional photographers often use cameras containing 15 million pixels.

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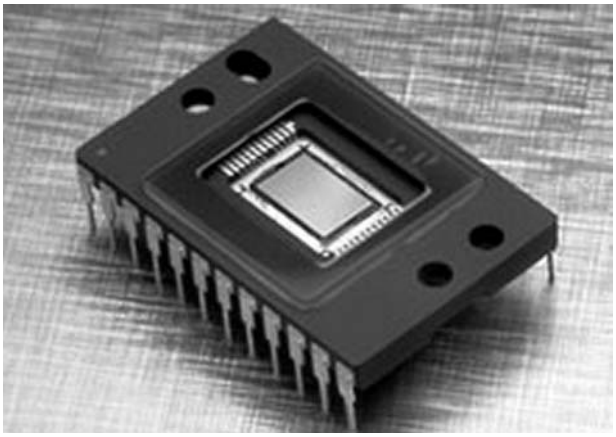


Figure 2.1. A CCD sensor; the light-sensitive silicon chip that forms the basis of many CCD cameras. This example is the KAF-0402E that appears in the popular SBIG ST7-ME camera. Image credit: Santa Barbara Instruments Group.

So, we have a regular grid of millions of light-sensitive pixels. That's a good start, but there are other important aspects of the image to be considered, such as whether the image is color or monochrome, what the spatial resolution is and how many shades of color (or gray, in the case of a monochrome image) the resultant image contains.

Imagine if you took an image where the full Moon just fitted into the sensor. To determine the resolution – the ability to record fine detail – of the image you would divide the width of the Moon into arc seconds (which is, conveniently, roughly 1/2 degree or 1800 arc seconds) by the number of pixels across the image. For many modern digital cameras this might give a result of the order of 1–2 arc seconds per pixel. However, it's best to determine the field of view of a sensor before buying it, and fortunately, there is a simple method related to the physical size of the pixels. You will find that, typically, pixel sizes vary from as small as 4 microns (a micron is one-thousandth of a millimeter wide) to around 25 microns. The pixel size will normally be found on the website of the camera manufacturer.

The way to estimate the resolution of a telescope/sensor combination is to do the calculation that follows. Don't worry, this isn't as bad as it sounds – all the trigonometry has been done for you in creating the number 206 – see below.

1. Multiply the size of your pixel (using microns) by 206.
2. Divide the number you obtained in stage 1 by the aperture of the telescope or camera lens (using millimeters).
3. Divide the number you obtained in stage 2 by the focal ratio of your telescope.

Not painful, and it yields an answer measured in arc seconds per pixel.
For those of you who like formulas, this is equivalent to:

$$\text{Resolution} = \frac{\text{Pixel size} \times 206}{\text{Focal ratio} \times \text{Aperture}}$$

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where pixel size is expressed in microns and the focal length is expressed in millimeters. Note that a focal ratio has no units, it's just a number. If you do a calculation and get silly results check that you have got the other units right. Using a focal length expressed in feet or pixel size expressed in inches or furlongs is not going to work. Note: 1 inch = 25.4 mm.

If the value is not that required for a given purpose, an optical device called a Barlow lens can be employed to increase it, or another optical device called a focal reducer used to decrease it.

As an example; consider a telescope of 200 mm aperture with a focal ratio f/6.3 used with a camera boasting 10 micron pixels:

Stage 1. $10 \times 206 = 2060$
Stage 2. $2060 / 6.3 = 326.9$
Stage 3. $326.9 / 200 = 1.63$.

So the resolution of each pixel is 1.63 arc seconds.

For those uncomfortable with math, Tables 2.1 and 2.2 provide some typical values for popular telescope and lens systems.

Table 2.1. The sky coverage – resolution – of each pixel when using telescopes

Aperture (mm)	Focal ratio (f/)	Resolution 7.5 micron pixel	Resolution 10 micron pixel	Resolution 20 micron pixel
60	15	1.71	2.28	4.56
114	8	1.69	2.25	4.51
150	8	1.28	1.71	3.41
200	4.8	1.61	2.15	4.29
200	6.3	1.23	1.64	3.27
200	8	0.96	1.28	2.56
200	10	0.77	1.03	2.05
250	4.8	1.29	1.72	3.44
250	6.3	0.98	1.31	2.61
250	10	0.62	0.83	1.65
300	6.3	0.81	1.08	2.16
300	10	0.51	0.68	1.36

Table 2.2. The sky coverage – resolution – of each pixel when using camera lenses

Focal length (mm)	Resolution 7.5 micron pixel	Resolution 10 micron pixel	Resolution 20 micron pixel
28	55.2	73.6	147
35	44.1	58.8	118
70	22.1	29.4	58.9
135	11.4	15.2	30.4
200	7.72	10.3	20.6
300	5.15	6.86	13.7

As we now know the size of each pixel in our sensor in terms of arc seconds, we can readily derive the region of sky covered by our image. It will be the resolution of each pixel multiplied by the number of pixels across the sensor's width. As before, let's take it in stages.

1. Multiply the resolution of sensor pixel (using arc seconds) by the number of pixels along the axis.
2. Divide the number you got from stage 1 by 3,600.

As a formula this is:

$$\text{Coverage} = \frac{\text{Pixel Resolution} \times \text{Number of pixels}}{3{,}600}$$

So, as an example, if we consider the LX200 mentioned earlier, our pixel size is 1.63 arc seconds and the width of our image is 1200 pixels:

Stage 1. $1.63 \times 1200 = 1956$
Stage 2. $1956 / 3600 = 0.543$;

then the sky coverage amounts to a bit more than half a degree.

Now the catch is that if you wanted pictures with even better resolution – as you would for detailed lunar or planetary imaging – you could use a Barlow lens which, in effect, magnifies the image that appears at the focal plane, or you would employ a sensor with smaller pixels. So a pixel size of 1 arc second per pixel would become 0.5 arc seconds with a ×2 Barlow lens and 0.33, 0.25, 0.2 arc seconds with a ×3, ×4, ×5 Barlow lenses, respectively. Similarly, focal reducers can be used to reduce the effective magnification of the scope. These are generally more limited in their effect upon magnification, with a factor of ×0.5 or ×0.33 being typical. With a ×0.5 reducer in place, a 1 arc second pixel would become a 2 arc second pixel.

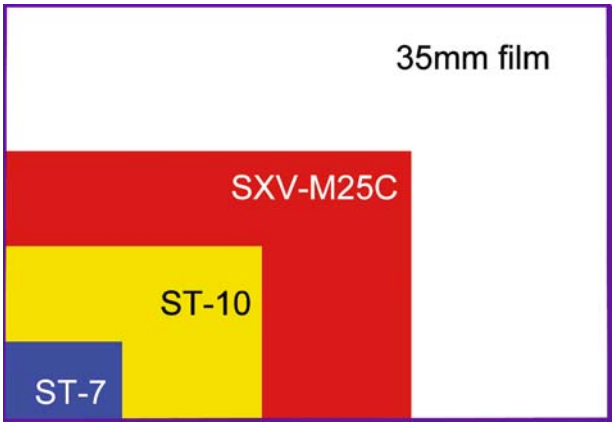


Figure 2.2. The relative sizes of the sensors found in some well-known cameras; the SBIG ST-7, the SBIG ST-10 and the Starlight Xpress SXV-M25C. These are compared against the size of film emulsion. Some sensors are now as big as 35 mm film, but they are still rather expensive. Image credit: Grant Privett.

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Be sure to bear in mind the fact that the resolution values we have calculated represent only the theoretical resolution of the sensor pixels with a given telescope/optics combination. The actual resolution achieved may be constrained by the resolving power of your telescope, and just as importantly, the steadiness of the atmosphere you are observing through. It is a rare night indeed in the UK or much of the US that telescopes get to perform to their full potential – it appears to be pretty much reserved for island mountains, Antartica and the high plateaus of Chile. On a turbulent night your pixels will still have the same angular resolution spacing but all sharp edges or features within the image will be blurred by the atmosphere.

As examples, a 75 mm (3 inch) aperture will be able to distinguish between two equally bright stars approximately 1.5 arc seconds apart, while a 200 mm (8 inch) aperture will do the same with stars 0.6 arc seconds across. Unfortunately, in urban areas the air turbulence will reduce this to a varying figure of the order of 2–3 arc seconds.

Image sampling is another area worth considering. If you are imaging the planets or are simply imaging star fields you will find that the most aesthetically pleasing results are obtained only when the image is over-sampled. That is to say you are operating with a camera that has a higher resolution than the finest feature you wish or hope to observe. For example, if you are looking at a double star whose components are separated by 3 arc seconds you would just be able to resolve it with an imaging sensor/telescopes combination where the pixels are of 3 arc second resolution, but the image would look pretty awful. A much nicer result would be obtained if the camera employed had a resolution of 1 arc second or less. In the 3 arc second resolution image the stars will be very blocky and angular, at best showing the double star as two bright pixels adjacent to each other, with most stars represented by a single pixel. With below 1 arc second resolution the component of the double star will appear as minute circles or crosses of light with a dark space clearly separating the double star. The down side of this is that if you use the same telescope for both images the higher resolution image would be rather dimmer, as the light from the star must now be spread out over 9 (3×3) times as many pixels. Obviously to overcome this you can take longer exposures or stack images – but more of this later. The upside, and it is considerable, is that over-sampling allows stacked planetary images to clearly show tiny features such as Encke's division on Saturn – a very narrow gap in the rings that eludes most visual observers. Thierry Legault and some others have imaged features on the moons of Jupiter (diameter < 2 arc seconds) when working at a focal ratio of more than 40.

As a general rule choose a pixel size, Barlow lens/focal reducer, telescope combination that has a resolution that is at least twice as fine as the smallest feature you hope to image. This reasonably intuitive rule, more formally known as the Nyquist limit, can be derived from some rather lengthy mathematics involving Fourier transforms which the reader will find discussed in the standard texts on image processing mentioned in the references section. Obviously it can be taken too far. If you over-sample too much, the light will be so spread out that it's difficult to tell if there is anything in the picture at all.

Another defining characteristic of an image is the extent to which it resolves differences in intensity. If we take the monochrome image case first, we find that it is

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usually expressed by describing an image as of 8, 12, 14 or 16 bits resolution. For those unfamiliar with "bits" they refer to the way numbers are stored in computer memory. The larger the number of bits employed in storing a number, the larger the number that can be stored. In the case of imagery it often refers to the number of gray levels that the camera can detect between a totally black scene – when no light has been received – and a perfectly white scene – when the sensor has recorded as much light as it can cope with. Table 2.3 shows the most common values.

These days monochrome CCD cameras generally operate at 16 bits, with a few still using 12 or 14 bits and some older auto-guider cameras employing 8 bits. Some cameras at professional observatories now use 24 bits per pixel (or more) but those are not generally available on the commercial market. It should be noted that 14 bits represents the minimum number of bits required to allow sophisticated image enhancement techniques to be undertaken without artifacts becoming apparent in the resultant image. You can work with 12 bit imagery, but it will limit what you can hope to get from the results.

However, the situation is different – and slightly confusing – for color cameras such as webcams, DSLRs and some CCDs, in that the number of bits the image is recorded in may be quoted as 24, 36 or 48 bits. This is because each pixel of the output image will have been generated using information from three closely spaced pixels on the sensor; one each of red, green and blue. So for each pixel of a 36 bit camera, the intensity of the red light sampled will have been determined to 12 bit accuracy as will the values for the other colors. Adding together these three sets of 12 bits makes up the 36 bits mentioned. The number defines the ability of the camera to resolve differences in the total light intensity, while the ratios between the values found for each pixel will define the hue of color recorded. Obviously, it might be expected that the best possible results would only be obtained using 36 or 48 bits per pixel images that permit a wider range of pixel brightness values. Yet, when multiple images are stacked, this potential limitation is dramatically overcome as the plethora of exquisite planetary images taken with 24 bit cameras so graphically testify. It is perhaps significant that the well-known planetary imagers Damien Peach and Martin Mobberley have recently moved over to using the Lumenera LU 75 cameras (12 bit) from a Philips ToUCam to improve their pictures still further.

Table 2.3. Shades of gray resolvable in images of various "bits" of accuracy

Bits	Discernible shades of gray
8	256
10	1024
12	4096
14	16384
16	65536



http://www.springer.com/978-1-84628-580-6

Creating and Enhancing Digital Astro Images

Privett, G.

2007, XII, 142 p. 88 illus., 39 illus. in color., Softcover
ISBN: 978-1-84628-580-6