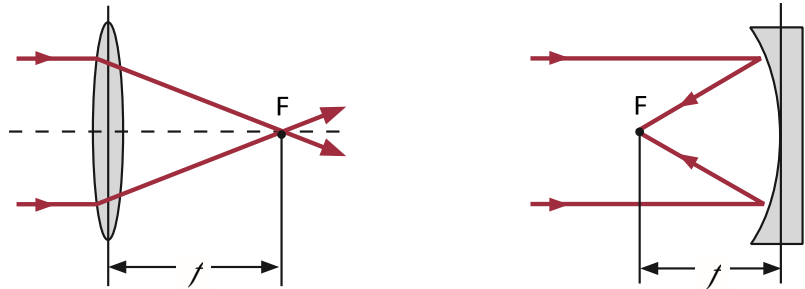


Resolving the night sky with *SPiRiT*

Focal length

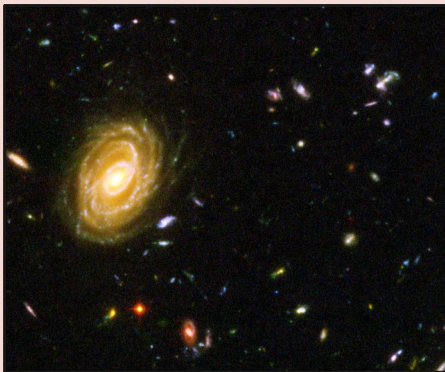
Telescopes come in many different sizes and designs. Focal length is an important characteristic that determines how a telescope is used.



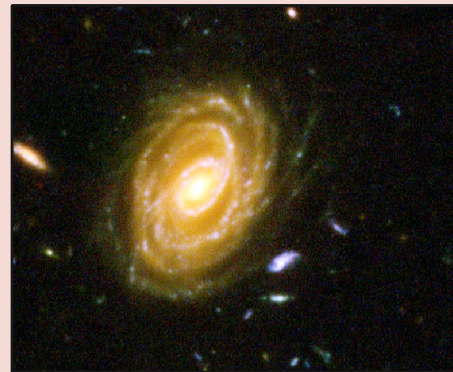
The focal length (f) of a telescope is the distance to the point (F) where light rays from an object are brought to focus after hitting the primary mirror or lens. It is determined by the design and size of the telescope's optics. In general, telescopes with long focal length provide a more magnified image and narrower field of view, while telescopes with short focal length have less magnification, but a wider field of view.

Survey instruments and wide-field imaging systems often have short focal length to take in as much sky as possible. Long focal length telescopes are best suited to objects with small angular sizes, such as planets and distant galaxies, as they provide more native magnification.

field of view versus magnification



large field of view

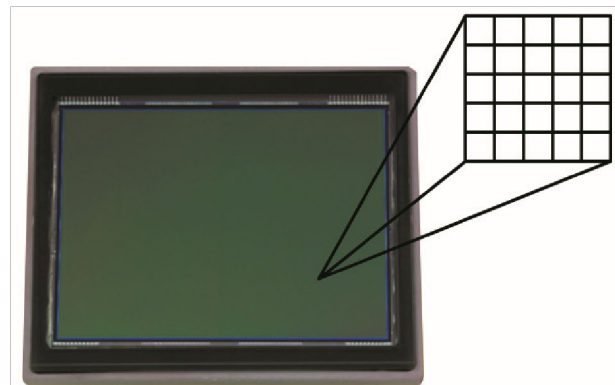


higher magnification

image: SA, ESA, S. Beckwith (STScI) and the HUDF Team

CCD sensors: the basics

An image sensor is a square or rectangular array of millions of pixels that turn light into electric charge. They are found in digital still and video cameras, and have an important role in imaging for astronomy. Two main types are used: CCD (charge-coupled device) and CMOS (complementary metal oxide semiconductor). CCD sensors are most often used in astronomical imaging cameras, whereas CMOS sensors are used in consumer digital cameras.


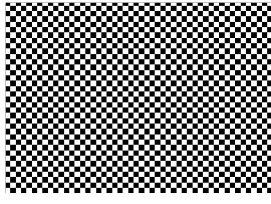
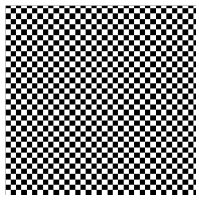
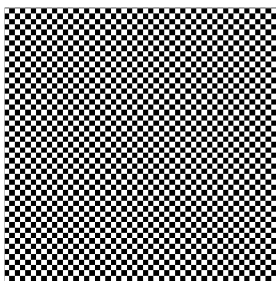


A CCD sensor is comprised of millions of individual pixels

There are many types of imaging sensors. Their size can be described two ways:

- dimensions (width and length) of the array, in millimetres; and
- number of pixels that make up the sensor, in megapixels (millions of pixels).

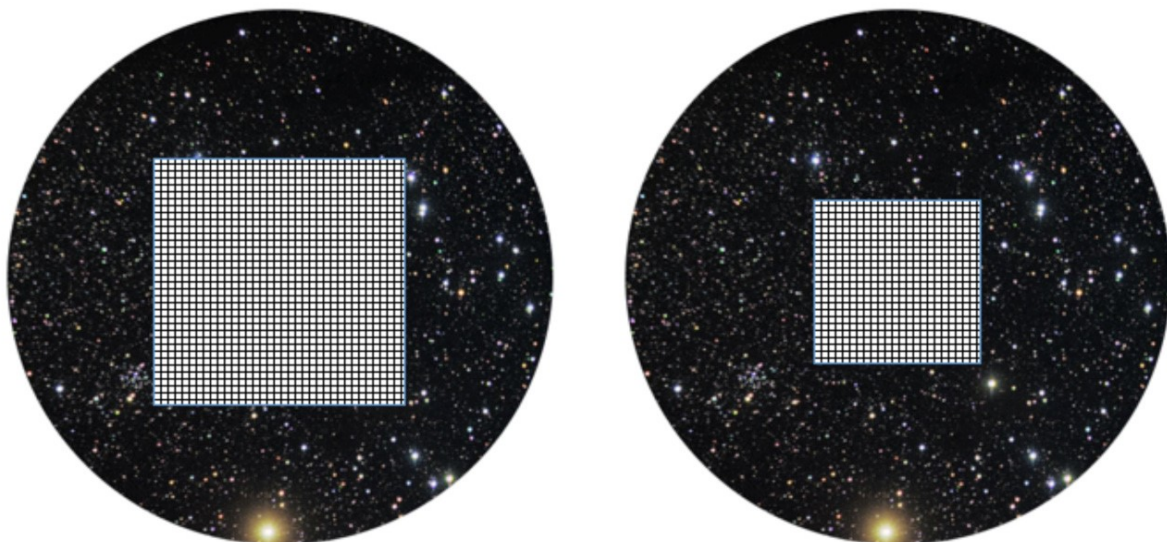
Pixels are always small, but they vary in size, from less than 4 μm to over 20 μm (1 μm = 0.001 mm).

sensor (actual size)	application	sensor size	pixels	pixel size
	typical consumer digital camera	7 mm x 7 mm	15 million	2 μm
	high-end digital SLR camera	25 mm x 35 mm	20 million	9 μm
	<i>SPIRIT I</i> camera	25 mm x 25 mm	1 million	24 μm
	<i>SPIRIT II</i> camera	36 mm x 36 mm	16 million	9 μm

Characteristics of image sensors used in typical cameras and the *SPIRIT* imaging systems

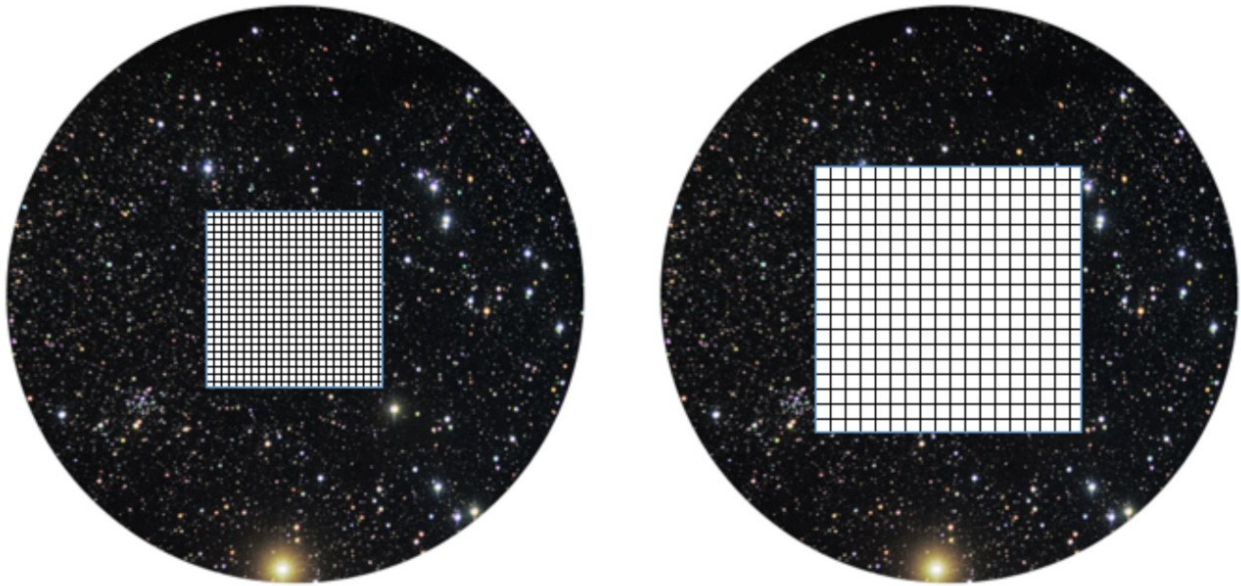
SPIRIT I uses a one-megapixel, square CCD sensor with an array of 1024 \times 1024 pixels. Individual pixels are 24 μm in size, so the size of the sensor itself is about 25 mm \times 25 mm. In the world of digital imaging this is considered comparatively large.

For any given telescope, a large sensor takes in more sky than a small sensor.



The sensor on the left captures more of the image than the sensor on the right. It has a larger 'field of view'.

It's not just the number of pixels, but also the size of pixels that determines the field of view of a CCD sensor. A sensor with 6 μm pixels needs sixteen times as many pixels to provide the same field of view as a 24 μm sensor. However, with sixteen times as many pixels in the same area, a 4096 \times 4096 array can resolve smaller details in distant objects. In imaging, such a sensor is described as having greater resolution.



These sensors have the same field of view, but the sensor on the left captures images with more detail than the sensor on the right. It has greater resolution.

It's not all about resolution

Conventional digital cameras use very small pixel, high-resolution sensors, often 10 megapixels or more. So why not use large sensors with very small pixels in astronomy?

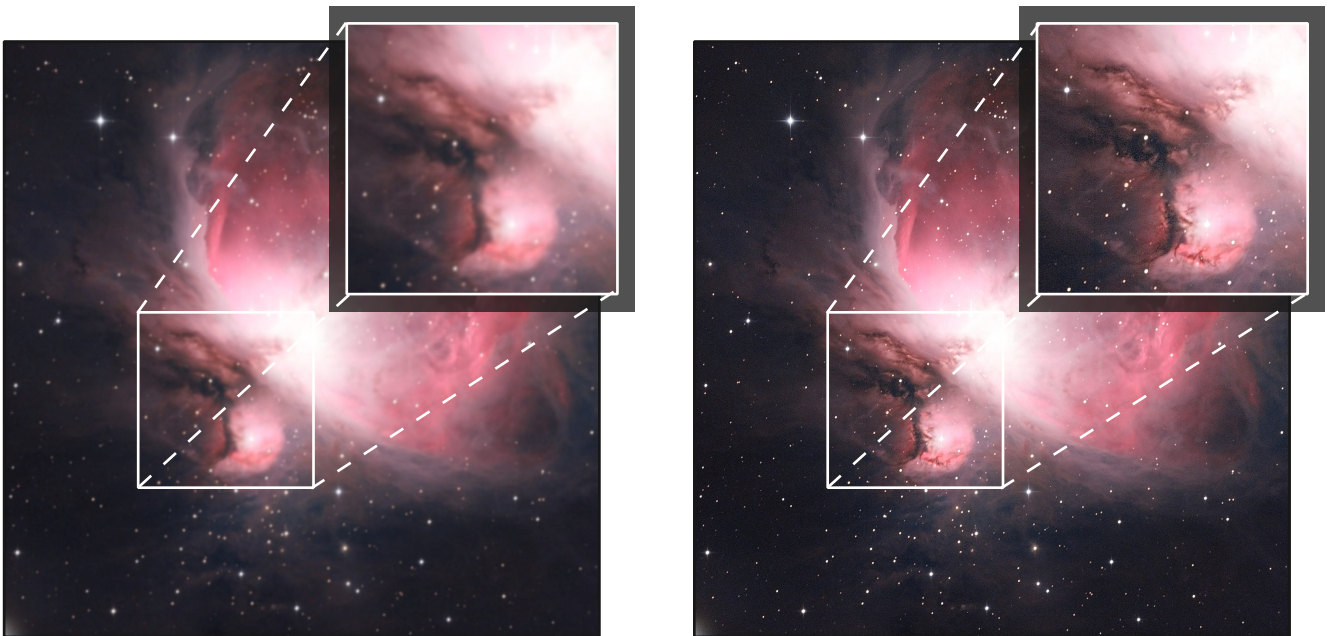
Increased resolution comes at a price. In astronomy, where extremely faint objects are imaged, it can be a disadvantage to use sensors with very small pixels because they are less sensitive to light than large pixels. A large pixel presents more 'area' to a given source of light, and gathers more photons per pixel, for a given exposure time. A CCD camera with 24 μm pixels can image a faint object in much less time than a camera with 6 μm pixels. This is an advantage if you need to image many objects in an efficient manner, or if you're trying to detect a faint source under challenging sky conditions.

Sensitivity is sometimes more important than resolution in astronomical CCD imaging.

Both field of view and resolution need to be known to understand the capabilities of any telescope. As well as helping to determine exposure times, these values are used to calculate the angular size of objects that have been imaged. Field of view and resolution depend on a telescope's design as well as characteristics of its CCD sensor.

Seeing the detail

The most misunderstood concepts of telescope design are those that deal with magnification and resolving power. It is not magnifying power of a telescope that determines detail in an image, but resolving power. Larger telescopes are capable of higher resolutions, which translate into fine, 'close-up' detail seen in images acquired by telescopes such as the Anglo Australian Telescope, or the Keck telescope in Hawaii. Both of these are reflecting telescopes that use very large primary mirrors.



These images of the Orion Nebula (M42) have the same magnification, but the high resolving power of the telescope that took the image on the right results in an image with considerably more detail.

A telescope's size is also sometimes referred to as its light-gathering ability. When you think about it, a large telescope really does 'gather more light' than a small telescope.

Pixel scale

An important measurement in a modern telescope imaging system is its pixel scale. This refers to the amount of sky taken in by each pixel on a CCD sensor. It is measured in units of angle, usually arcseconds.

There are 90 degrees of sky from horizon to zenith.

1 degree = 60 arcminutes.

1 arcminute = 60 arcseconds. 1

arcsecond is very small!

object	typical size
Moon	30 arcminutes
Crab Nebula (M1)	420 x 290 arcseconds
Saturn	18 arcseconds
Alpha Centauri	0.007 arcseconds

Pixel scale is a critical measurement when characterising a telescope's resolution and field of view. It helps determine types of target for which a telescope is best suited.

Pixel scale is calculated from a telescope's focal length and the size of pixels used in its CCD sensor, using the formula:

$$\text{pixel scale} = 206.265 \times \frac{\text{pixel size } (\mu\text{m})}{\text{focal length (mm)}}$$

The constant, 206.265, is a factor to convert μm to mm and radians to arcseconds.

SPIRIT II has a focal length of approximately 3000 mm and uses a sensor with 9 μm pixels. So it has a pixel scale of $206.265 \times 9 / 3000 = 0.6$ arcseconds. In other words, each pixel captures light from a 0.6 arcsecond patch of sky.

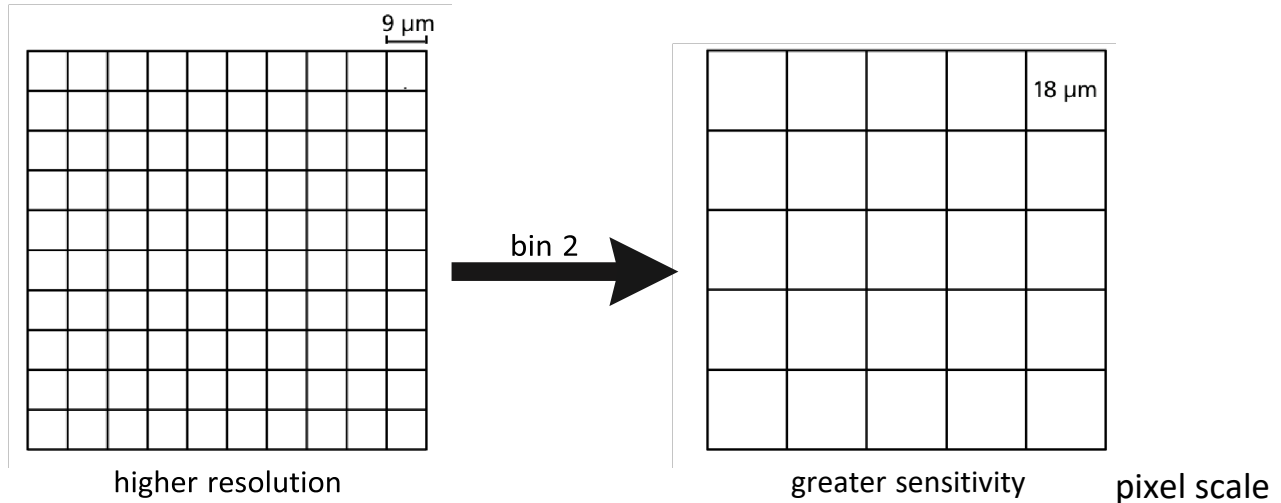
To calculate field of view, multiply pixel scale by width of CCD sensor in pixels. *SPIRIT II* has a 4096 x 4096 sensor, so field of view is:

$$0.6 \times 4096 = 42 \text{ arcminutes (about } 0.7^\circ\text{)}.$$

Binning: matching pixel scale to imaging conditions

Under excellent sky conditions of a mountaintop in a remote location, *SPIRIT II* could theoretically resolve details in an astronomical object with diameter less than 1 arcsecond. However, turbulent and light-polluted skies significantly affect the telescope's performance to the extent that it can be difficult to resolve details smaller than 3 arcseconds. Under these conditions it doesn't make sense to use a high-resolution CCD sensor, particularly when this leads to reduced sensitivity.

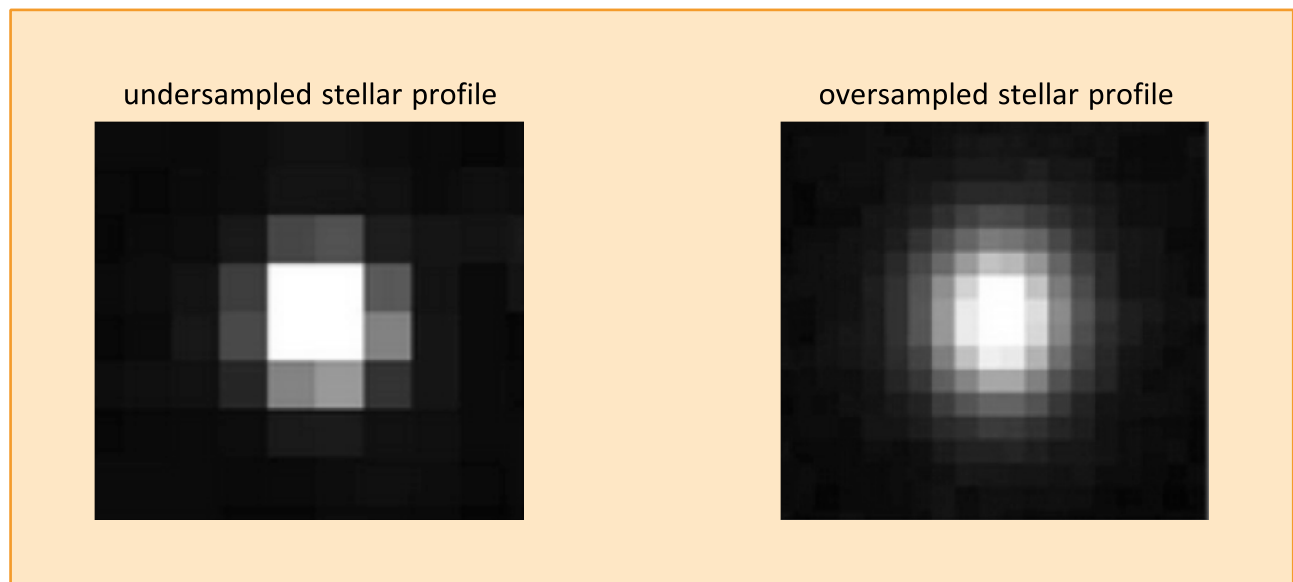
Fortunately, all astronomical CCD cameras provide a solution to this problem. Pixel binning is a means by which individual pixels in an array can be grouped so they behave as if the camera had a smaller number of larger pixels.



A setting of bin 2 transforms the *SPIRIT II* camera into a 4 megapixel camera with pixels that are 18 μm across. Effective pixel scale is 1.2 arcseconds, which approaches the best resolution expected under Perth's light-polluted skies.

Bin 3 creates a 1.8 megapixel camera with 27 μm pixels and a pixel scale of 1.8 arcseconds. The characteristics of *SPIRIT II* at bin 3 are close to those of *SPIRIT I* at bin 1, which uses a 1 megapixel, 24 μm sensor.

Excessive binning produces pixelated images with square-shaped stars, known as 'under-sampling'. It is better to slightly over-sample than under-sample, so binning beyond 3 is not recommended with any of the *SPIRIT* telescopes.



Altering binning does not change the field of view as total area of the sensor does not change. *SPIRIT II* has a 42 arcminute field of view, regardless of binning mode.

Binning is generally unnecessary with *SPIRIT I* because of its large pixel size. Bin 2 can be used to acquire colour channels for an LRGB target, where resolution is only important for the luminance channel. In this case RGB channels provide colour data, not image detail. Most astronomical image processing applications can cope with a mix of bin 1 and bin 2 images.

Balancing sensitivity and resolution with target choice

Characteristics of an imaging system need to be balanced with intended use of a telescope. Small or bright objects benefit from smaller binning modes, because sensitivity is reduced and resolution increased. Large, faint and diffuse objects, such as galaxies and nebulae, benefit from higher binning modes that increase camera sensitivity.

A long focal length telescope can take advantage of larger pixels, but its field of view will be comparatively small compared to a short focal length telescope. Short focal length telescopes are better able to use high-resolution cameras before under-sampling becomes an issue, but the wide field of view may not suit objects with small angular sizes.

There is no telescope imaging system that does everything perfectly. Most telescopes are designed for specific tasks, such as survey work or high-resolution planetary imaging.

Imaging with *SPIRIT*

SPIRIT telescopes have been optimised to produce pleasing images of relatively large, deep-sky objects, such as nebulae, star clusters and galaxies.

SPIRIT I has a field of view of approximately 20 arc minutes. At Bin 1 it operates at a resolution of 1.2 arcseconds per pixel, which is ideal under skies at UWA.

SPIRIT II has a field of view of approximately 42 arc minutes. It operates best at Bin 2 (1.2 arcseconds per pixel) and Bin 3 (1.8 arcseconds per pixel).



deep sky image of galaxy NGC 253 taken with *SPIRIT I*