OBSERVATIONAL ASTRONOMY

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Lecture 8

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Methods of Observations

- Imaging
- Photometry
- Spectroscopy
- Polarimetry
- Interferometry

The Primary Tools of Astronomy

Light is the only thing we can work with. What can we do with it?

- Imaging – we can take "pictures" of the things we see. But pictures alone tend to lack the "quantitative" aspect that is needed for most serious scientific studies.
- Photometry – the technique that measures the relative *amounts* of light in different wavelength ranges.
  But these ranges are too wide to provide detailed information on the light's spectral distribution.
- Spectroscopy (spectrophotometry) – the most informative technique of light analysis, that measures how much light an object produces at various wavelengths of light.

Imaging

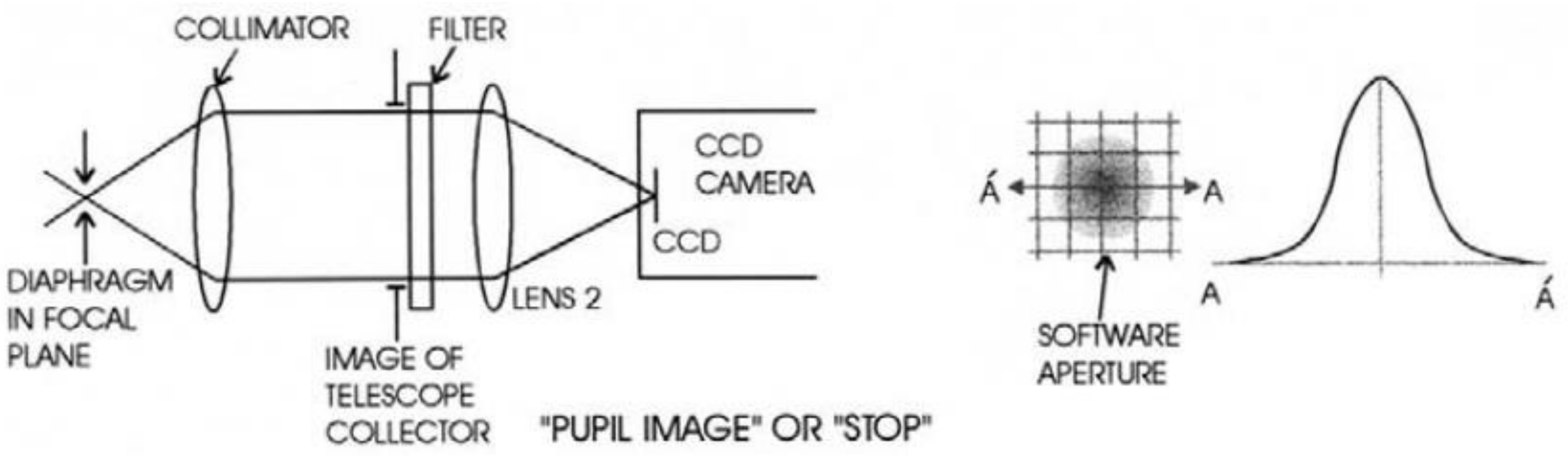
- Mapping the distribution of celestial sources on the sky in order to locate the position of source precisely – astrometry.
- Getting information on the source's form and that of its local environment.

Imaging: Pixel sampling

Pixel sampling and matching to the plate scale.

Two issues:

1. Maximizing observing efficiency → more light onto a pixel → less integration time
2. No compromise to the ability to obtain accurate brightness measurements



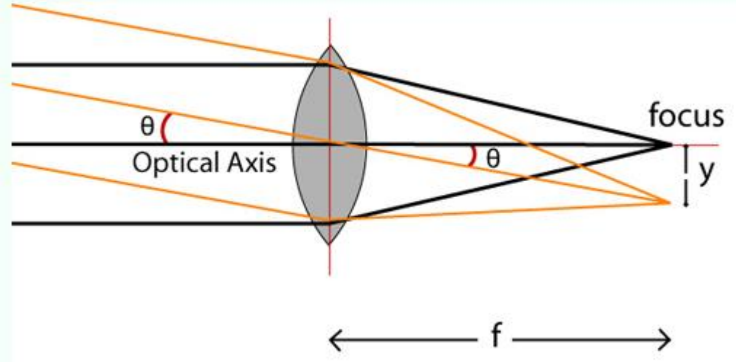
Imaging: specifications of a telescope

Two concepts used by astronomers when describing the specifications of a telescope are the plate scale and the focal ratio:

- **Plate scale**, *ps*, relates the angular size of an object on the sky, θ, to the size of its image in the focal plane, y. The term comes from the time when photographic plates were used to record images.

$$\tan\theta \approx \theta = \frac{y}{f} \quad \rightarrow \quad ps = \frac{\theta}{y} = \frac{1}{f}$$

where θ is measured in radians



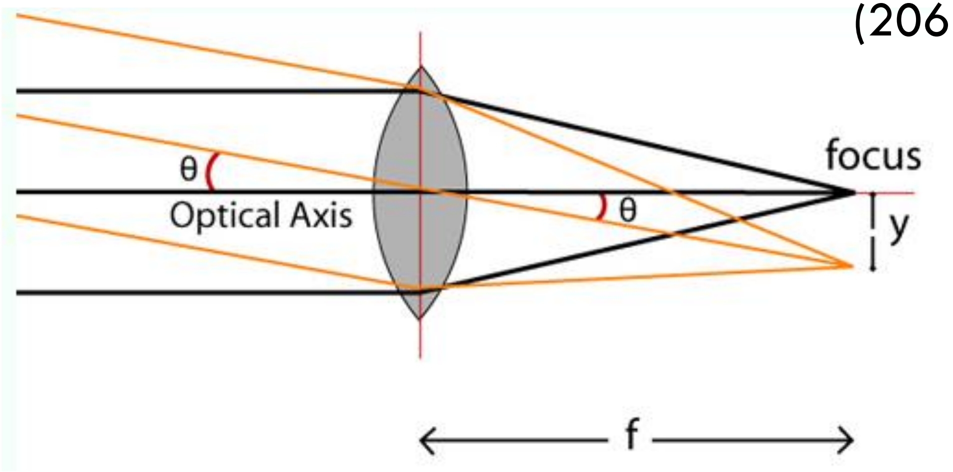
- If an astronomer wishes to study an object of angular size in **high** spatial detail, *ps* needs to be small, and therefore a **long** focal-length telescope is required.

Imaging: Plate scale

- Astronomers usually refer to the plate scale in units of arcseconds per mm. Then, the plate scale of the telescope:

$$ps = \frac{206265}{f} \,[''/\text{mm}]$$

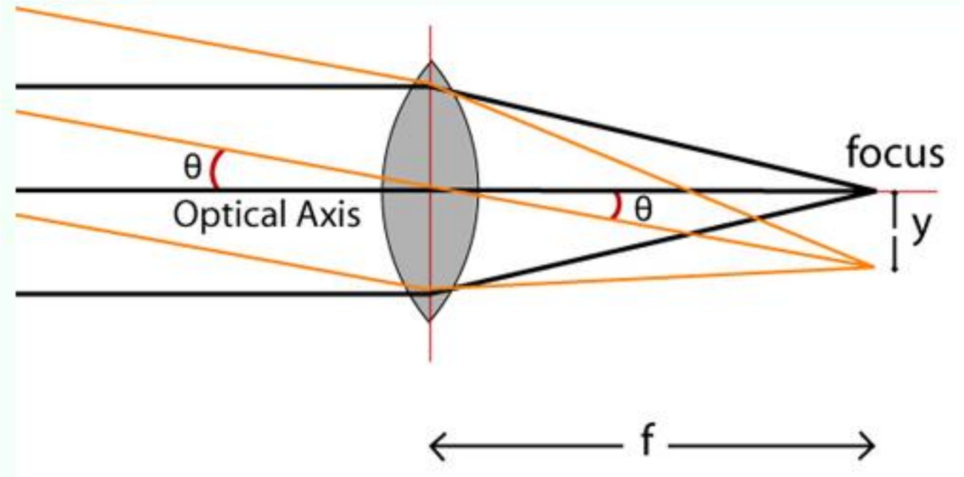
(206265 is ~ the number of arcseconds in 1 radian)



- For direct imaging, the angle on the sky subtended by the detector pixel is $\theta = ps\ d_{pix}$, where d_{pix} is the physical pixel size in mm.

Imaging: Focal ratio

- **Focal ratio** is defined as the ratio of the focal length of the telescope to its diameter, i.e. *f/D.*



- The term is often used in photography, where it refers to the "speed" of the camera. The larger the focal ratio, the "slower" the camera, as the amount of light falling on a given area of the focal plane is smaller. For larger *f* at fixed *D*, the plate scale *ps* is smaller and hence the light is spread out over a larger area. For a "faster" camera, the reverse is true.

Imaging

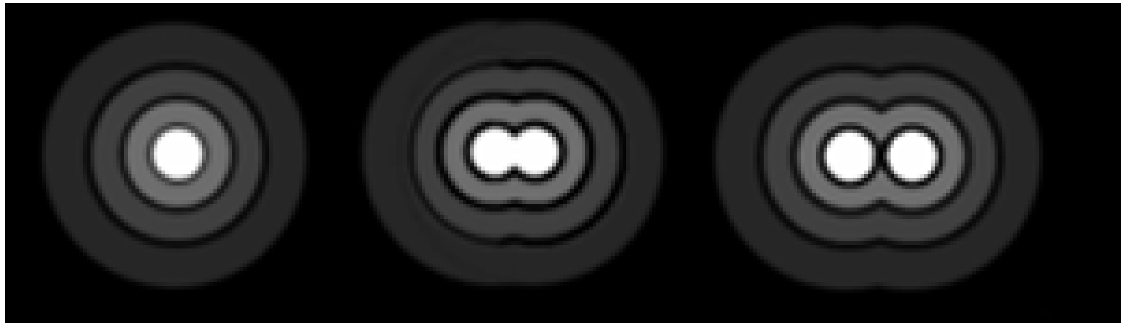
The spatial resolution element may be determined by seeing conditions or by optical constrains.

- In general, the image is critically sampled if there are about 2 pixels (the Nyquist limit) across the resolution element
- Or the image is oversampled if there are a few pixels (~4-5) across the resolution element

The resolution element: diffraction limit and seeing!

Effect of diffraction on image resolution

- Two distant point sources through a circular aperture:

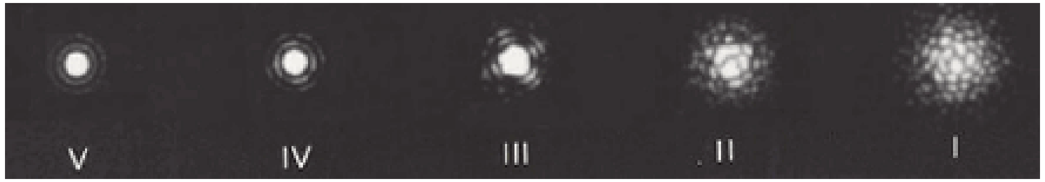


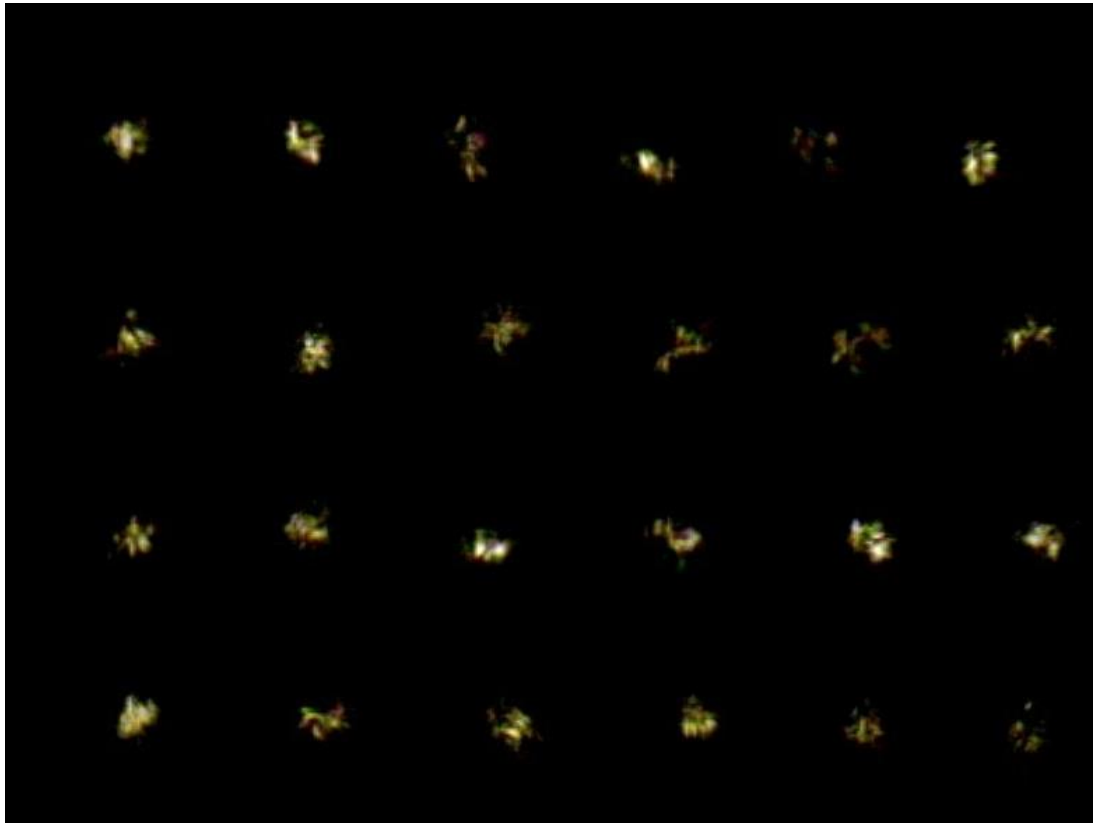
- **The Rayleigh criterion:** two images are just resolved if the centre of the first Airy pattern is superimposed on the 1st dark ring of the 2nd pattern.
- According to Rayleigh criterion, the minimum resolvable angular separation or angular limit of resolution is given by:

$$\vartheta \cong 1.22\, \lambda / D \text{ (radians)}$$

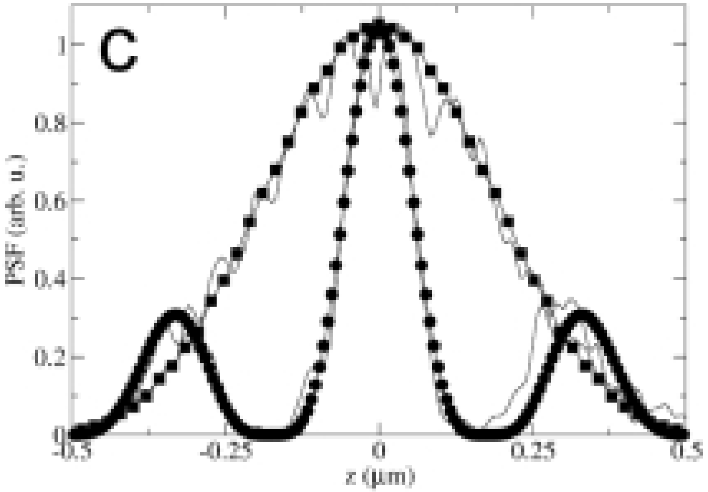
λ is wavelength and D is the diameter of the aperture

Imaging and Seeing





Ground-based telescope resolution is determined by the atmosphere, rather than aperture size. The central maxima of a Point Spread Function (PSF) expanded by turbulence is called *seeing disc*, and its FWHM is *seeing*.

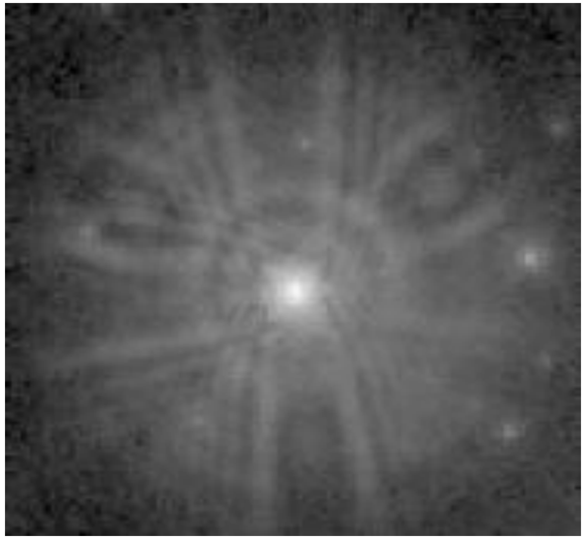


PSF, convolution & deconvolution (1)

- The **Point Spread Function** (PSF) is the main brick that builds up the whole acquired image.

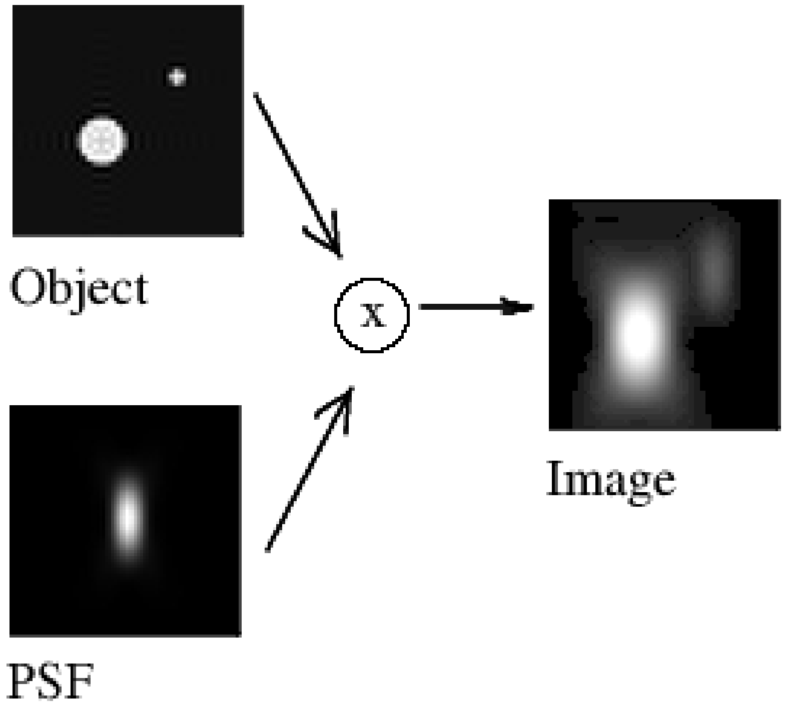
- The PSF is the image of a single point object (rescaled to make its integral all over the space equal 1). The degree of spreading (blurring) in the image of this point object is a measure for the quality of an image.

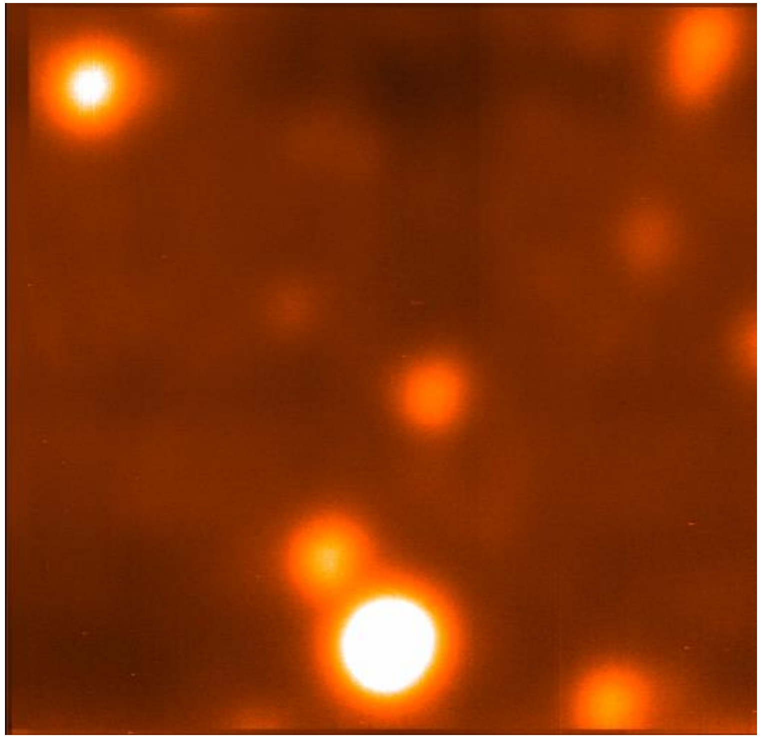
- The point spread function of Hubble Space Telescope's WFPC camera before corrections were applied to its optical system.



PSF, convolution & deconvolution (2)

- **Convolution:** The process is mathematically described by a convolution equation of the form $g = h * f$, where the image *g* arises from the convolution of the real light sources *f* (the object) and the PSF *h*.
- You can imagine that an image is formed in your telescope by *replacing* every original Sub Resolution light source by its Point Spread Function (multiplied by the correspondent intensity).





PSF, convolution & deconvolution (3)

- **Deconvolution (Image restoration)** is the recovery of images from raw data. Deconvolution is an "inverse" problem: the object of deconvolution is to find the solution of a convolution equation of the form

$$h * f + \varepsilon = g,$$

where h is PSF, g is some recorded image, ε is noise that has entered our recorded signal, and f is the real light source that should be recovered.

- The algorithms and methods are:
  - **Richardson – Lucy** deconvolution
  - **Maximum Entropy Method**

Lucky Imaging

- Lucky Imaging is an effective technique for delivering near-diffraction-limited imaging on ground-based telescopes.
- The basic principle is that the atmospheric turbulence that normally limits the resolution of ground-based observations is a statistical process. If images are taken fast enough to freeze the motion caused by the turbulence we find that a significant number of frames are very sharp indeed where the statistical fluctuations are minimal.
- By combining these sharp images we can produce a much better one than is normally possible from the ground.

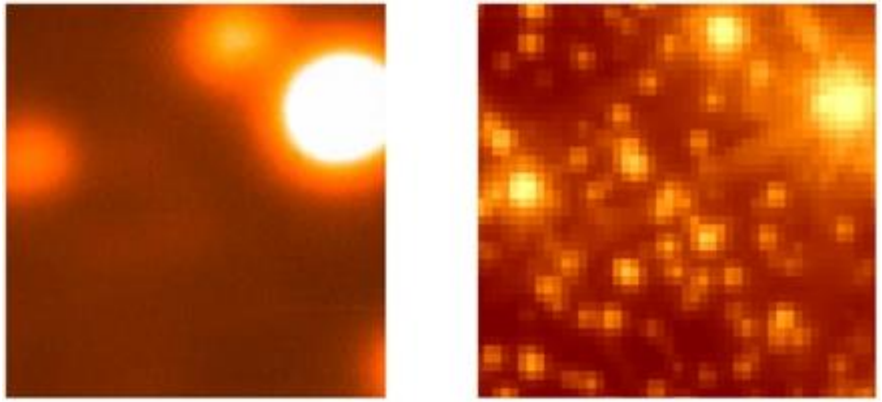


Image processing (1)

- A CCD image is built up from three signal sources:
  - object: photons imaged onto each pixel of the CCD
  - dark current: thermal electrons collected in each pixel during the exposure
  - bias: a low level electrical signal added to each pixel during image readout

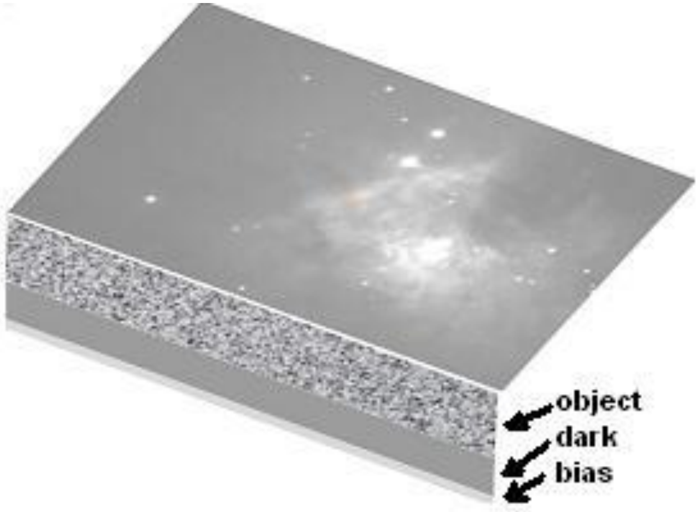
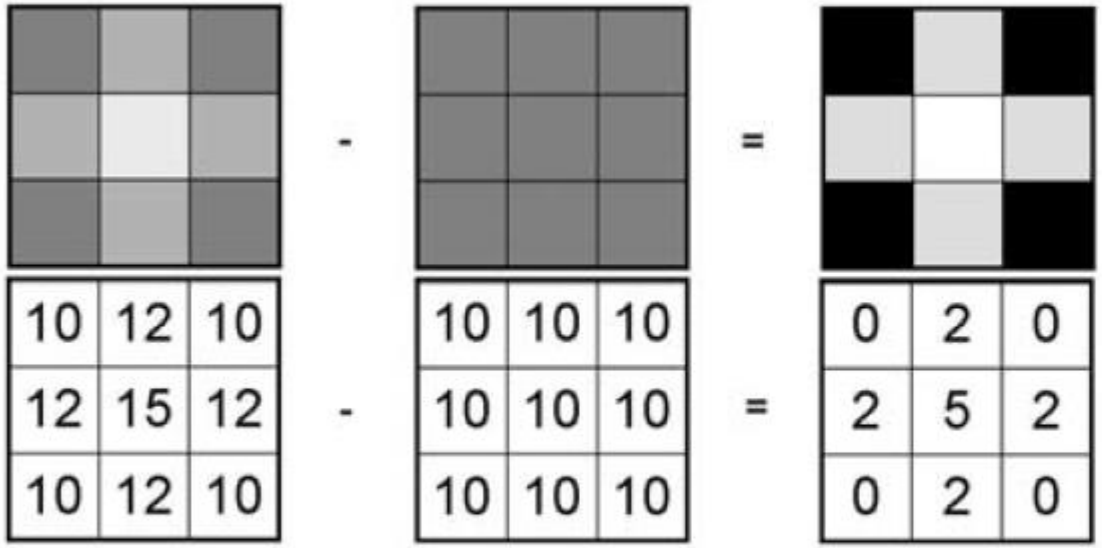


Image processing (2)

- Most processing steps must be carried out pixel by pixel



A simple operation on digital image data to subtract one frame from another.

Image processing (3)

- **Darks:**
  - In order to remove the accumulated background due to thermal dark current, it is usual to take several "darks" which are images taken with the CCD camera shutter closed. These darks should be of the same exposure time and camera temperature as the object exposure to be dark subtracted.
  - It is best to take a set of dark images and then to combine them to get a "master" dark based on the average of the dark set.
    [Note: it is usual to "median combine"]

Image processing (4)

- **Bias:**
  - In addition to thermal noise, each pixel charge will carry with it a fixed offset voltage value called the bias. Thus even if the output coming from the CCD were exactly zero electrons for every pixel, there would still be a signal that would vary from pixel to pixel in a repeatable fashion. An bias frame is one taken to determine this bias pattern.
  - Again, it is best to take a set of bias images and then to combine them to get a "master" bias based on the average of the bias set.

Image processing (5)

- **Flat Fielding:**
  each pixel on the CCD may have a different sensitivity to incoming photons due to small variations in individual pixel dimensions and quantum efficiency. For precision photometry it is necessary to calibrate such pixel-to-pixel variations and this is the function of "flat fielding". There are several different approaches but the two that are applicable to most observatories are
  - Dome Flats: A uniformly illuminated target is installed in the dome or attached to the front of the telescope
  - Sky Flats: Images are taken of the sky which is assumed to be uniform in brightness over the (usually small) field of view of the CCD

Image processing (6)

- **Flat Fielding:**
  - Take an exposure of a source which will uniformly illuminate each pixel of the CCD;
  - Pixel sensitivity (and perhaps other effects) will be a function of wavelength so separate flat fields are needed for each filter;
  - Use a long enough exposure time to fill pixels to more than 50% of their full well capacity.

Image processing (7)

- **Flat Field** types:
  - Twilight Flat: Exposures of the twilight sky (well away from horizon). Can correct for all of the types of sensitivity variations but the twilight sky is typically much bluer than the typical program object.
  - Dome flat: Exposure of a special target, usually mounted on the dome (such a target is completely out of focus and thus effectively uniform). Does well on Pixel to Pixel variations, poorly on vignetting.
  - Sky Flat: Median combination (to remove stars) of many exposures of the night sky
    Good correction of vignetting, poor correction of Pixel to Pixel variation.
    Hard to get enough photons on CCD – exposures may be very long.

Image processing (8)

- **Flats:**
  - Take a number of dome or long exposure (5 to 10 seconds) twilight flats
  - Do Dark and Bias corrections for each image
  - Average or median combine to get high S/N image
  - Make a copy and smooth with a large area filter (25 x 25 pixels) to remove pixel to pixel variations
  - Divide high S/N image by smoothed image
  - Normalize to 1.00 at the center
  - Save as a 32- bit real image
- The result is your "pixel flat"

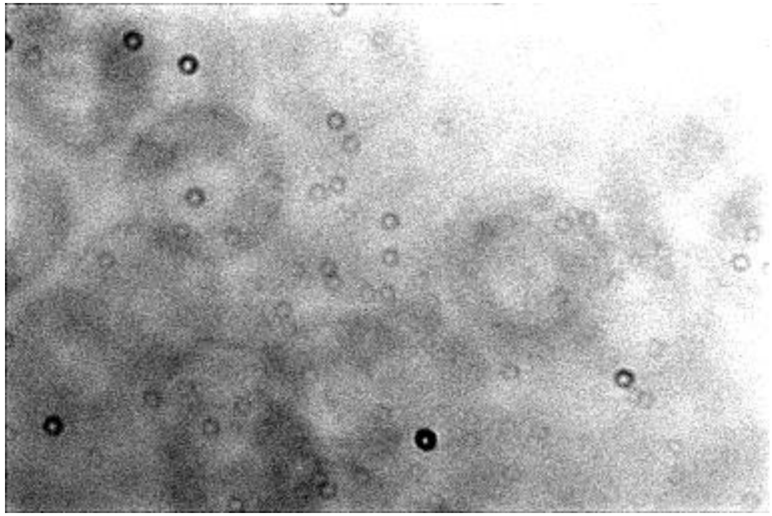


Image processing (9)

- Cleaned image after dark, bias, and flat-field corrections

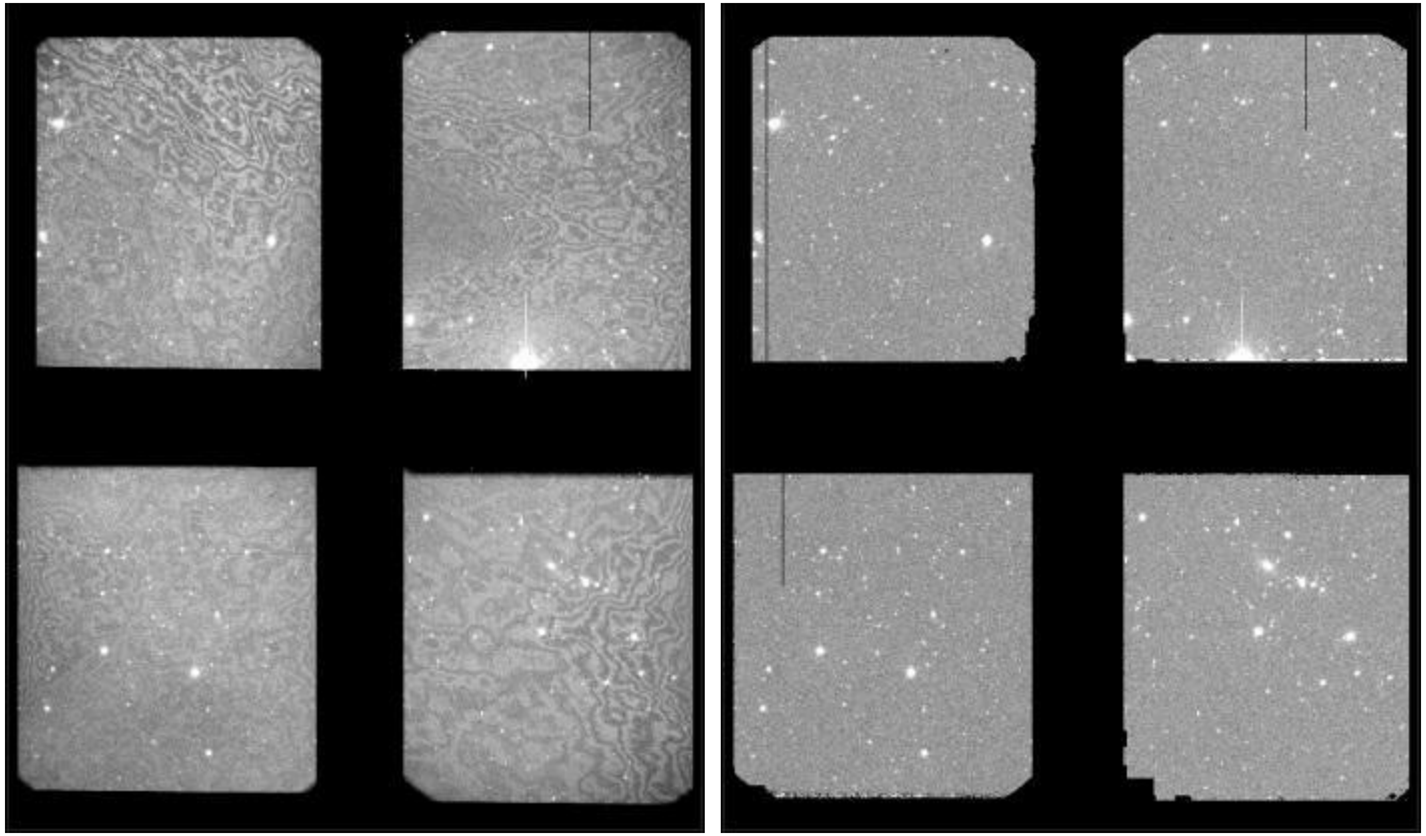


Image processing (10)

- **Summary:**
  - Start with raw image
  - Subtract dark and bias images
    - use high s/n "master bias" and "master dark" frames for best results
  - Divide by flat field
    - use high s/n "master flats" for best results
    - flats must have dark and bias removed

Image processing (11)

Do not forget! Cosmic Ray Events:

Image processing (12)

- There are several major computer packages:
  - IRAF
  - MIDAS
  - IDL (commercial)
  - Starlink

- Other Imaging Techniques are used in High-Energy Astronomy (we will not discuss the data reduction procedures adopted for high energy data):
  - HeaSoft

Physical limitations on the precision of photometric measurements (1)

- What we get out of our detectors?
- Have we taken enough data?
- How much longer should we observe?

The important quantity that compares the level of a desired signal to the level of background noise is

the Output Signal-to-Noise Ratio (S/N)

Physical limitations on the precision of photometric measurements (2)

- Let's consider a stationary source of light (a star) with an average photon flux at the detector of N_* photons per second.
- The intensity of a source will produce the **average** number of photons, but the actual number collected will be more than, equal to, or less than the average, and their distribution about that average will be **a Poisson distribution**.

- The "counts" accumulated in a CCD pixel (or similar detectors) have **a Poisson distribution**.

Physical limitations on the precision of photometric measurements (3)

- The standard deviation of the photon noise is equal to the square root of the average number of photons (Poisson statistics). The *Input* **Signal-to-Noise Ratio** is then

$$S/N = \frac{N_*}{\sqrt{N_*}} = \sqrt{N_*}$$

where N_* is the average number of photons collected.

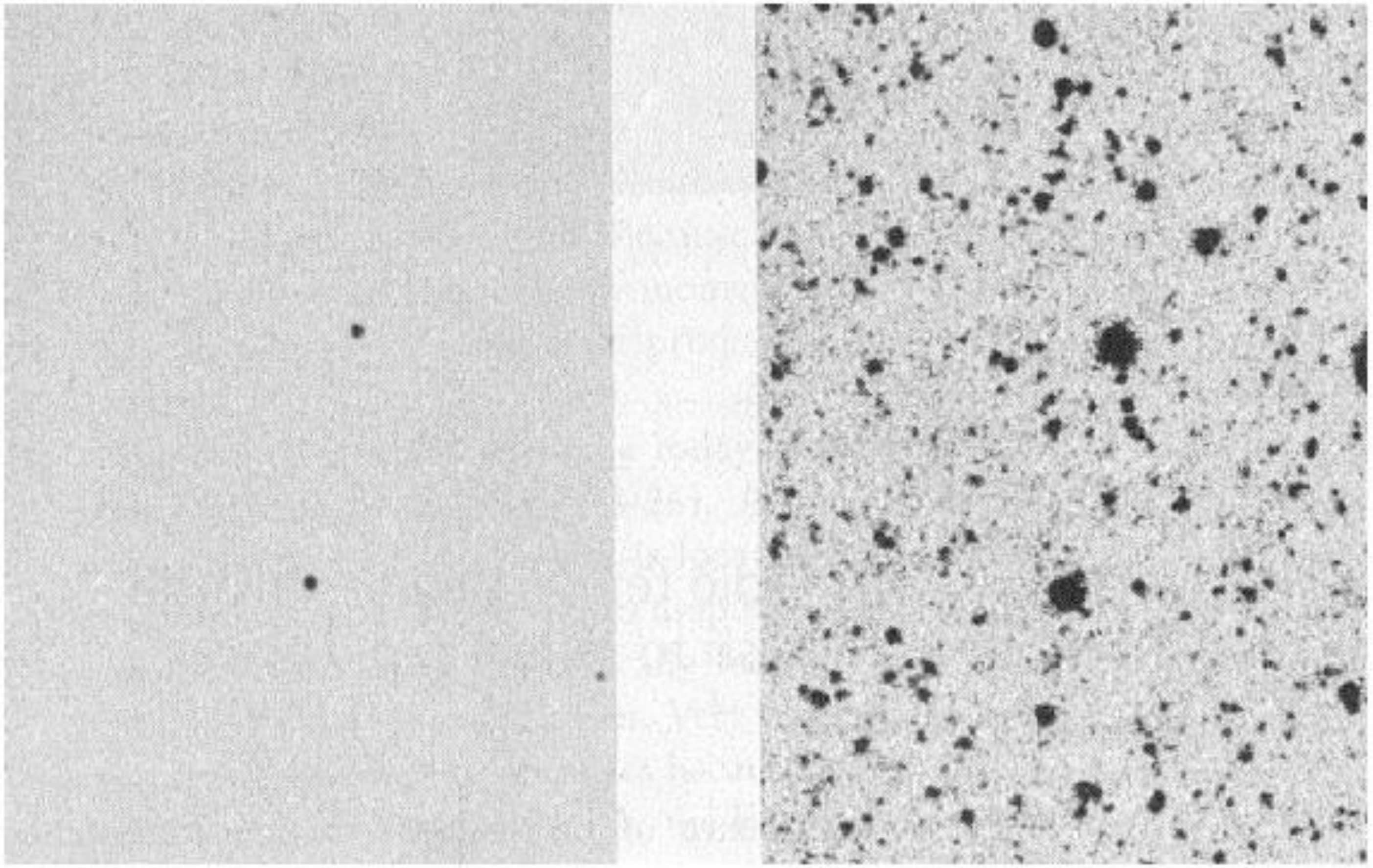
- When N_* is very large, the signal-to-noise ratio is very large as well. It can be seen that photon noise becomes more important when the number of photons collected is **small**.

Physical limitations on the precision of photometric measurements (4)

- In the absence of sky background and readout noise it would be simple to calculate S/N, we would integrate for some time, detect some 10000 photons, and have a signal to noise ratio of 100 or so.
- So, if we ignore the sky background it's a simple calculation, **but we can't**.

Physical limitations on the precision of photometric measurements (5)

Sky and readout noise can be significant.



Physical limitations on the precision of photometric measurements (6)

- In dark sky at a dark site (no moon, no reflected street light), the magnitude of a 1 arcsecond patch of sky in the *V* band is approximately V_{sky}=21.5 mag.

Thus, every square arcsecond of sky gives:

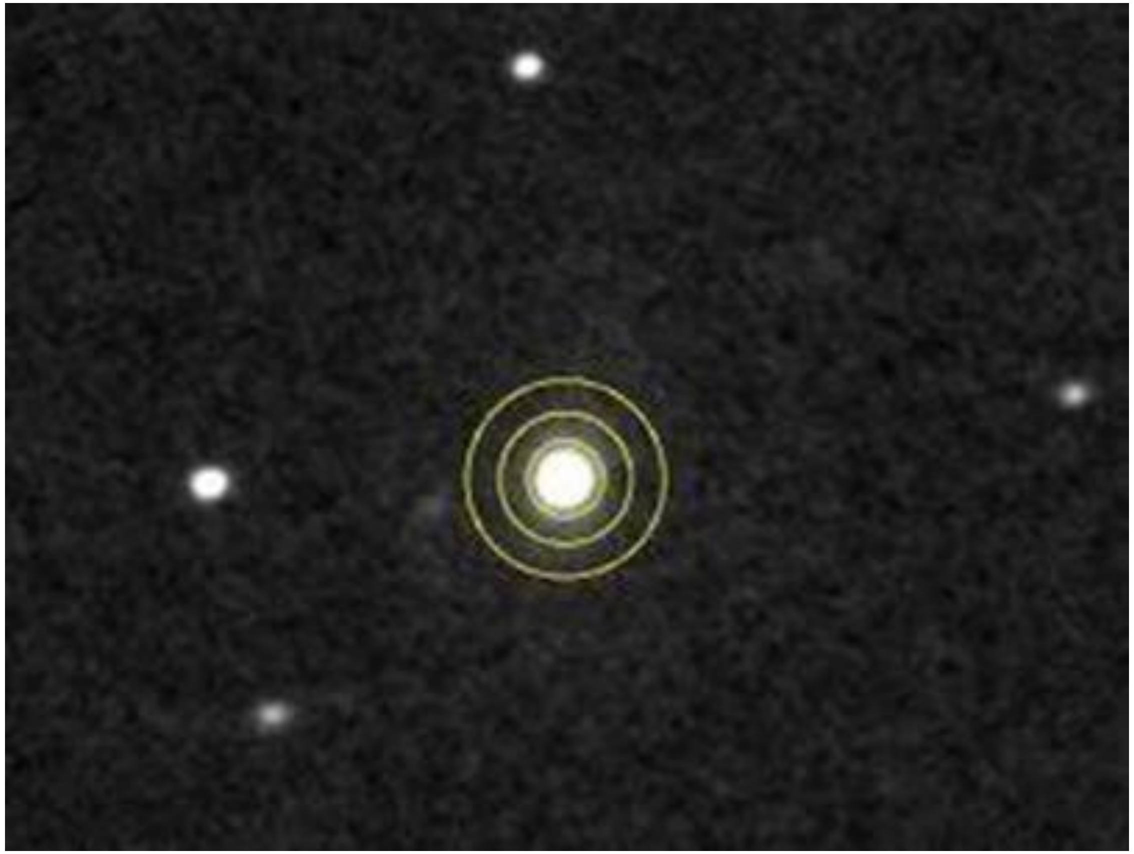
$$S_{sky} = 2.5\times10^{-3} \text{ photons} / (\text{cm}^2 \text{ arcsec}^2 \text{ second})$$

Physical limitations on the precision of photometric measurements (7)

- To calculate the ***Output* Signal-To-Noise Ratio** of an observation we need to know the signal, and all sources of noise. These are:
  - Photon noise (shot noise) from the signal;
  - Photon noise from the sky background under the signal;
  - Photon noise from the sky background measurement to be subtracted off;
  - Readout noise from all sources;
  - Fixed pattern noise;
  - Bias noise;
  - Dark current noise.

A case study of simple aperture photometry (1)

- We observe a star on a CCD detector, and process the data in the simplest way possible.
- An area centred on the star is defined to be the object area and is large enough to contain all the photons from that star.
- An equal area some distance away, which is found to be free of stars, is defined as the sky background area (sky aperture), and the sky background is measured from that.



A case study of simple aperture photometry (2)

- We will make some assumptions:
  - We have eliminated fixed pattern noise by dividing the image by a normalised long exposure of a uniform light source, this is called *a flat field*.
    We already discussed it on last Thursday.
  - Bias noise and dark current noise are negligible, as this is a cryogenically cooled, buried channel CCD.

Aperture photometry

- There are a number of parameters we need to take into account to calculate the signal which reaches the detector:
  - t – exposure time
  - β – angular size of a source (defined by the seeing)
  - D – diameter of the telescope
  - S_{sky} [photons / (cm^2 arcsec^2 second)] – brightness of the sky
  - η – quantum efficiency of a detector (QE)
  - f_* [photons / (cm^2 second)] – the source flux to be measured

Signal calculation (1)

- We start from the number of photons incident from this star, from the sky, and from the star + the sky:
  - $A \sim D^2$ is the telescope collecting area [cm^2]
  - $B \sim \beta^2$ is the source area on the sky [arcsec^2]

- $n_* \approx \eta D^2 t f_*$ – an average number of photons from the source
- $n_{sky} \approx \eta D^2 t \beta^2 S$ – an average number of photons from the sky
- $n_{*+sky} \approx \eta D^2 t (f_* + \beta^2 S)$ – an average number of photons from the source and the sky

Signal calculation (2)

- That is without the Readout noise and other detector noises. If we want to take them into account – we must add $N_d = n_d t$ to the right side of equations.

- There is also a geometric efficiency factor as part of the aperture of the telescope is blocked by the secondary mirror.

For a while, we will not take these factors into account.

Noise on the measurements

- Noise on the measurements is given by the square root of the number of photons:

$$\sigma_{*+sky} = \sqrt{n_{*+sky}}$$

$$n_* \approx n_{*+sky} - n_{sky}$$

$$\sigma_* = \sqrt{n_{*+sky} + n_{sky}} = \sqrt{n_* + 2n_{sky}}$$

(If x and y have independent random errors σ_x and σ_y , then the error in $z = x \pm y$ is $\sigma_z^2 = \sigma_x^2 + \sigma_y^2$)

Signal to Noise ratio (1)

$n_* \approx \eta\, D^2\, t\, f_*$

$$S/N = \frac{n_*}{\sigma_*} = \frac{n_*}{\sqrt{n_* + 2n_{sky}}} = \frac{\eta\, D\, t\, f_*}{\sqrt{\eta\, t\, (f_* + 2\, \beta^2\, S)}}$$

$n_{sky} \approx \eta\, D^2\, t\, \beta^2\, S$

Let's now consider two special cases:

- If the Source dominates over the Sky: $\mathbf{n_* \gg n_{sky}}$
- If the Sky noise dominates: $\mathbf{n_{sky} \gg n_*}$

Signal to Noise ratio (2)

$$S/N = \frac{n_*}{\sqrt{n_* + 2n_{sky}}} = \frac{\eta\, D\, t\, f_*}{\sqrt{\eta\, t\, (f_* + 2\,\beta^2\, S)}}$$

If the Source dominates over the Sky: $\mathbf{n_* \gg n_{sky}}$

$$S/N \cong \frac{n_*}{\sqrt{n_*}} = \sqrt{n_*} = D\sqrt{\eta\, t\, f_*}$$

$$f_{\min} \sim 1 \,/\, (D^2 t)$$ for the given S/N

the telescope aperture is most important!

Signal to Noise ratio (3)

$$S/N = \frac{n_*}{\sqrt{n_* + 2n_{sky}}} = \frac{\eta\, D\, t\, f_*}{\sqrt{\eta\, t\, (f_* + 2\,\beta^2 S)}}$$

If the Sky noise dominates: $n_{sky} \gg n_*$

$$S/N \cong \frac{n_*}{\sqrt{2n_{sky}}} = \frac{\eta\, D\, t\, f_*}{\sqrt{2\,\eta\;\, t\;\beta^2\, S}} = \frac{D\, f_*}{\beta}\sqrt{\frac{\eta\, t}{2\, S}}$$

$$f_{min} \sim \frac{\beta}{D}\sqrt{\frac{S}{t}} \text{ for the given S/N}$$

the seeing (angular size of a source) is most important!

Signal to Noise ratio (4)

Source dominates over the Sky	Sky noise dominates
$$S/N \cong D\sqrt{\eta\, t\, f_*}$$	$$S/N \cong \frac{D\, f_*}{\beta}\sqrt{\frac{\eta\, t}{2\, S}}$$
$$\boldsymbol{f_{\min} \sim \frac{1}{D^2 t}}$$	$$\boldsymbol{f_{\min} \sim \frac{\beta}{D}\sqrt{\frac{S}{t}}}$$
for the given S/N	for the given S/N

most important is

the telescope aperture	the seeing