McLean seminar

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5. Instrumentation and detectors

- Review the details of each class of instrument, i.e. layouts, basic relationship
- Introduce each major type of detectors

5.1 PHOTOMETERS AND CAMERAS

4 classes of astronomical instruments

photometers/cameras	measure the brightness and direction of radiation,
spectrometers	measure the distribution of brightness (or energy) as a function of wavelength
polarimeters	determine the degree of alignment of wave vibrations in a beam
interferometers	rely on coherent phase relationships to achieve interference effects before performing imaging or spectroscopy

X-ray to radio wavelengths (gamma ray?)
→following description applicable for UVOIR

5.1.1 Photoelectric photometers

photometer: device for measuring the apparent brightness of a source

transmission through the atmosphere (ground-based)
→ light has been collected by a telescope → measurement

・measure the power received per square meter integrated over all wavelengths (i.e., the irradiance (flux density?) E or astronomical flux S)

・limited to a band of wavelengths selected by means of an optical "filter"
→ Initially, colored glass filter, detector's own wavelength-dependent
→ Now, make an optical filter to pass any specific band
= "interference filters" multiple, very thin, dielectric layers deposited on the glass substrate.

・UBV system (Ultraviolet, Blue, Visual)

・Many filter systems → need to care how each system relates

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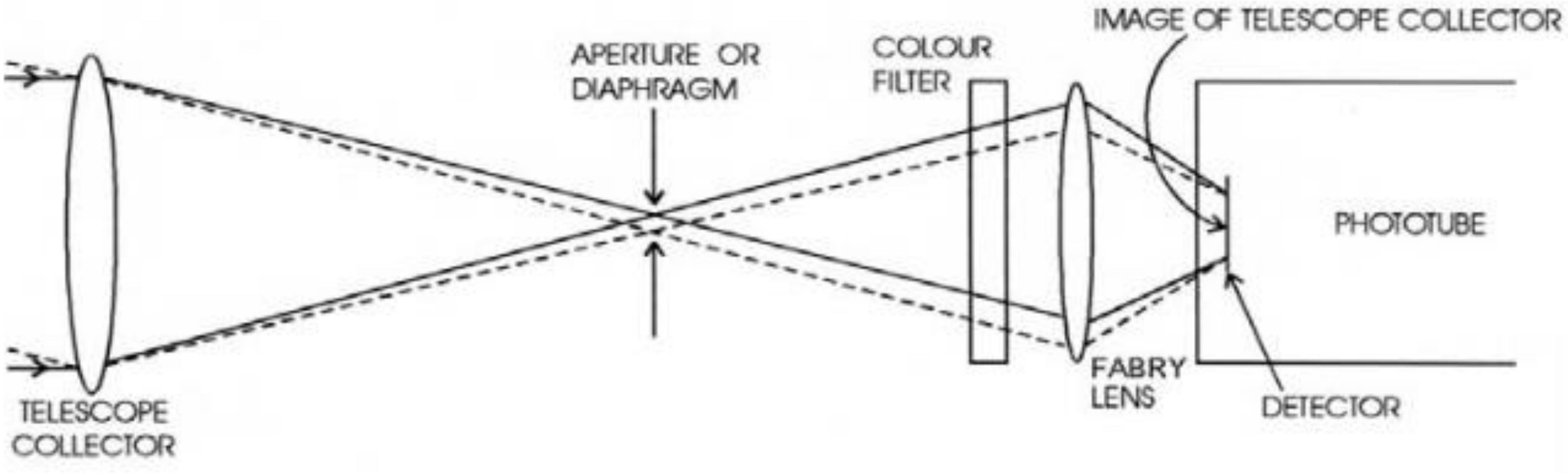
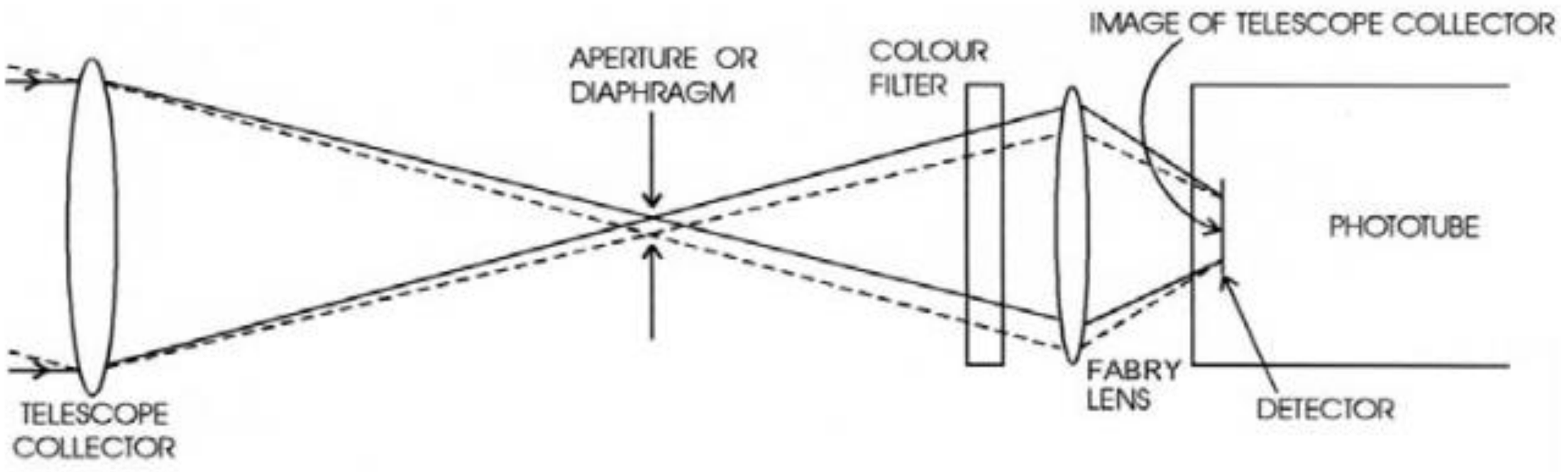
5.1.1 Photoelectric photometers



・individual stars → a detector with a single cell i.e. photomultiplier tube (PMT).
(Now replaced by CCD. Super-Kamiokande uses > 10k PMTs)

https://en.wikipedia.org/wiki/Photomultiplier_tube



・Light-Tight Box:

Encloses the entire system to prevent external light from interfering with measurements.

・Flange:

Connects the photometer to the telescope.

・Aperture or Diaphragm:

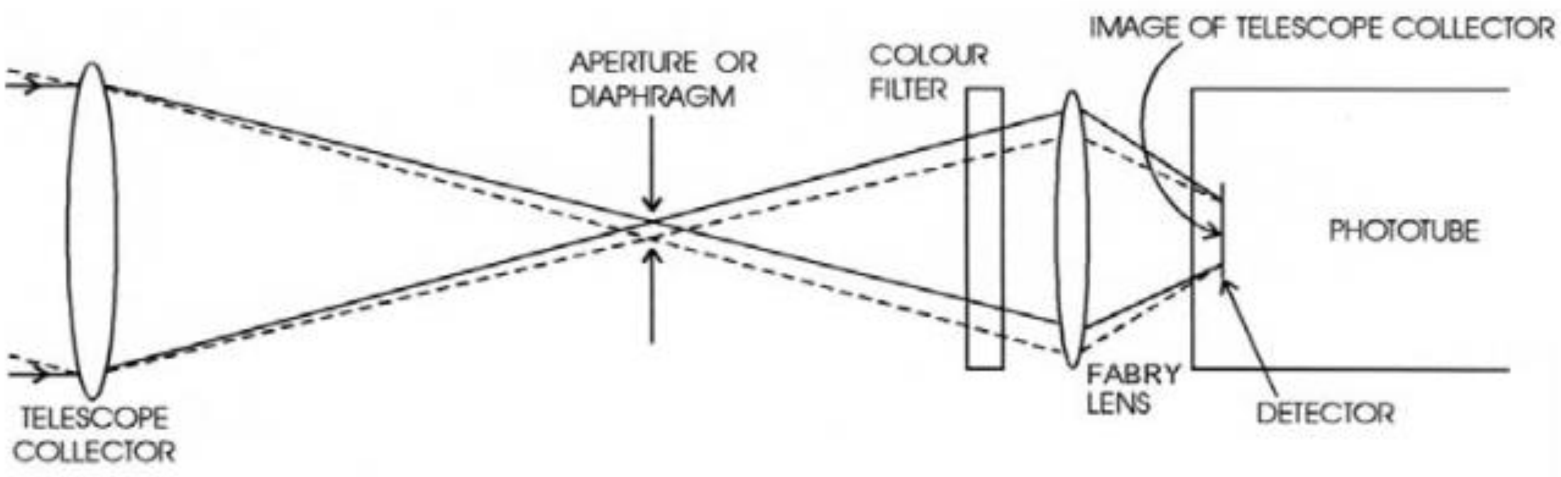
Isolates the light from the target star. The aperture size can be changed to match the seeing conditions and minimize background light.

・Photomultiplier Tube (PMT):

Detects the light and converts it into an electrical signal.

・Fabry Lens:

Creates an image of the telescope's primary mirror on the detector, ensuring stability in the light path regardless of star position within the aperture.



Light from the star remains stable on the detector even if the star drifts within the aperture. Light from the star is focused through the aperture, filter, and Fabry lens onto the PMT, producing a stable signal.

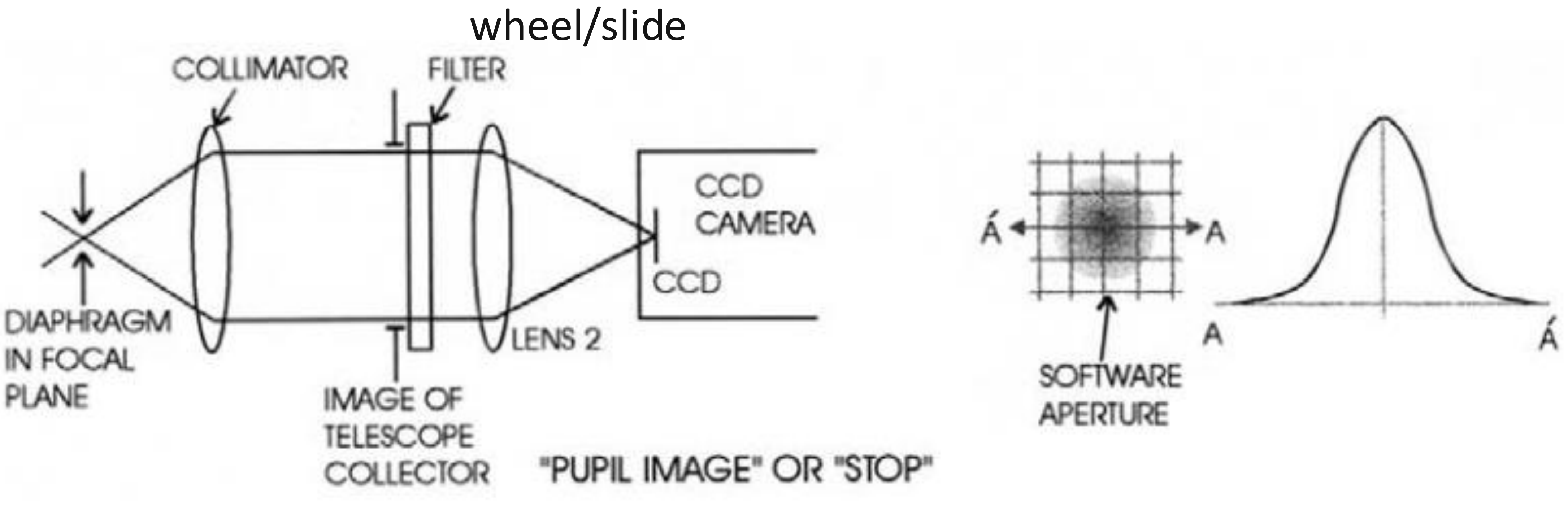
The PMT generates electron pulses proportional to the incoming light intensity. Pulses are amplified and filtered to remove noise before being counted and recorded.

PMTs are cooled to -20°C (some PMTs with high dark currents are cooled to -78°C)

High-Speed Photometry:
PMTs respond very quickly to changes in brightness, making them ideal for observing rapid variations in light from objects like pulsars or during occultations.

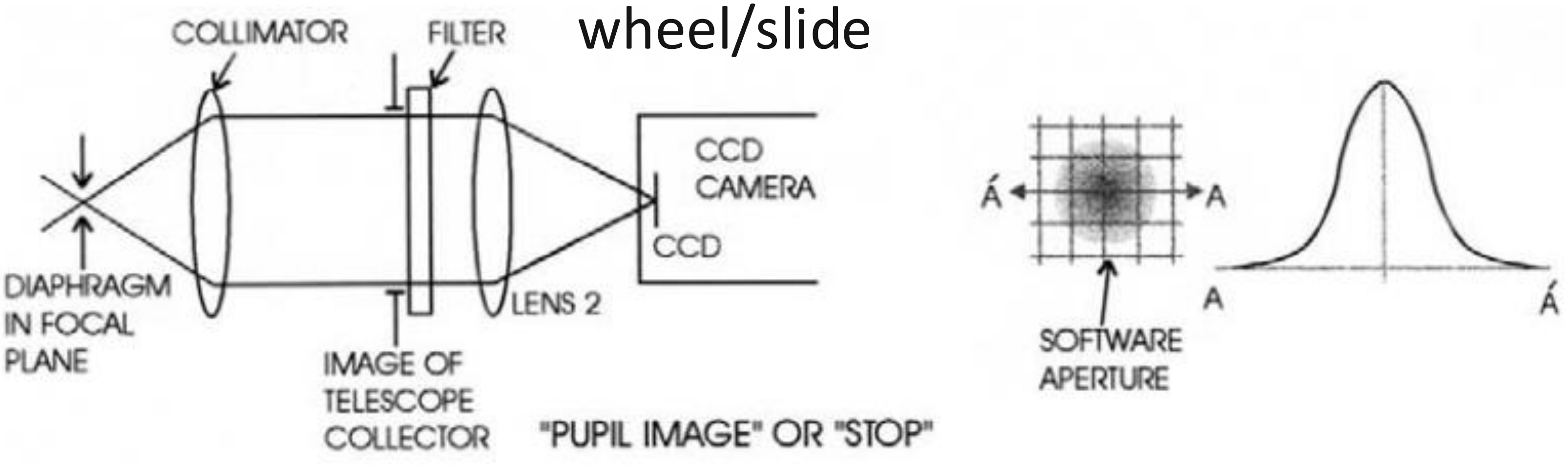
Polarization Measurements

5.1.2 Camera systems



・Simplest design = place detector (e.g. CCD) in the focal plane
・It is important to ensure that all filters have same optical path
→ avoid refocusing after filter change
→ difficult for very large telescope

5.1.2 Camera systems



・Alternative method

collimate the beam by placing a lens after the focal plane at a distance equal to its focal length and re-image the field onto the detector with a camera lens (or mirror)

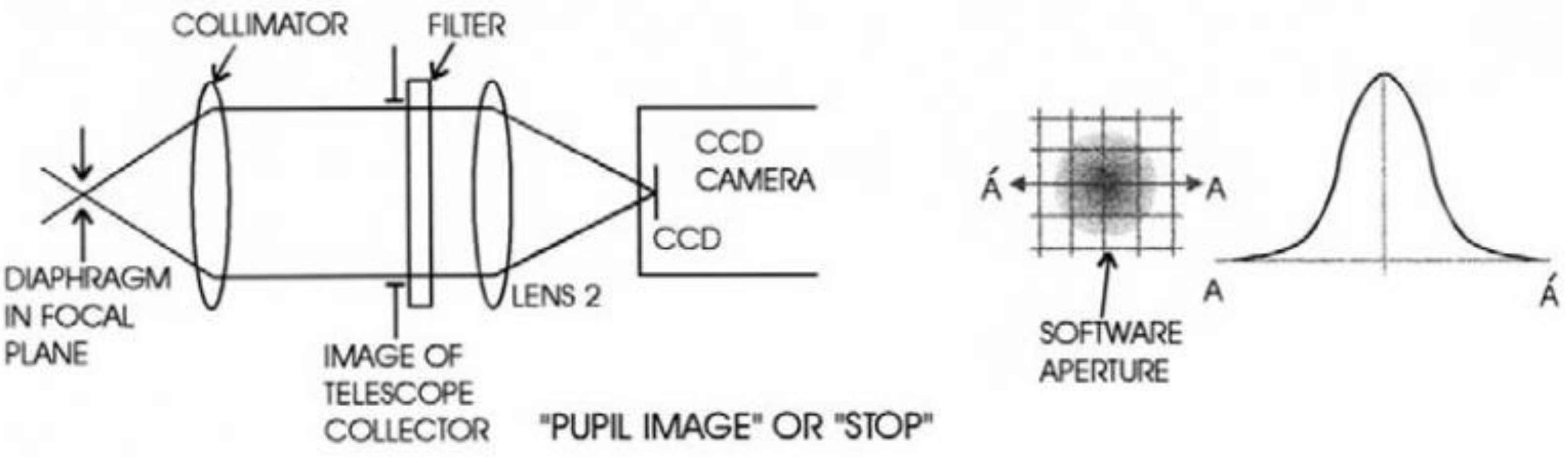
・Advantage

1. By selecting the focal lengths of the collimator and camera one can either magnify or reduce the plate scale / pixel scale (relates the angular field of view)
2. Filters of arbitrary thickness can be located in the parallel (collimated) beam
3. "stop" can be placed at the pupil image to reject stray light from outside the beam

→ For IR cameras "cold" stop = extremely important

5.1.2 Camera systems

wheel/slide



・Perform photometry

photometry is performed "after the fact" on the digital image

→ select an appropriately sized "software aperture" and sum up all the signals.

・Local sky background estimation → no separate measurement of the sky is needed

・normalize all the pixels to the same sensitivity / gain

5.1.3 Pixel sampling and matching to the plate scale

two issues for matching the spatial or spectral resolution element to the physical size of the detector pixels:

1. **Maximize observing efficiency**: more light, but minimize the exposure time
2. Without compromising the ability of the camera system: to perform very accurate brightness measurements (photometry)

The spatial resolution element maybe determined by seeing conditions or by optical constraints.

Nyquist sampling: 2 pix to the resolution element
Oversampling : > 5 pix to the resolution element

5.1.3 Pixel sampling and matching to the plate scale

In a spectrometer, entrance slit is determining factor

narrow slit → higher spectral resolution
wide slit (enough to cover the whole object) = highest efficiency is archived

・Plate scale calculation

$$(ps)_{\text{tel}} = \frac{206{,}265}{f_{\text{tel}}}$$

$$f_{\text{tel}} = D_{\text{tel}} \times F$$

f_cal: focal length /mm
D_tel: diameter
F: focal ratio or f/ number

Prime focus of 3.6 m CFHT 13.70''/mm
Cassegrain focus 7.33''/mm

For IR, focal ratio is larger (fainter/slower)
3.8 m UKIRT Cassegrain focus 1.52''/mm

Subaru:
Prime focus F/2.0
Cas: F/12.2
Nasmyth (Vis): F/12.6
Nasmyth (IR): F/13.6

5.1.3 Pixel sampling and matching to the plate scale

$$\theta = (ps)_{\text{tel}} d_{\text{pix}}$$

d_pix: the physical pixel size /mm
CCDs and NIR array detectors: 0.009 mm to 0.030 mm
HAWAII2-RG 0.018 mm (18 um)

Prime focus of 3.6 m CFHT 13.70"/mm
Cassegrain focus 7.33"/mm
20 um (0.020 mm) detector pixels
→0.27"/pix (prime), 0.15" / pix (Cass)

UKIRT 1.52"/mm
→ 0.03"/pixel

Compare these values with the image quality
to determine whether or not some optical magnification is required.

5.1.3 Pixel sampling and matching to the plate scale

- choose a value for the diameter of the seeing in seconds of arc;
- decide on the sampling ($p = 2$–5 pixels);
- divide seeing diameter by sampling factor to get angular size of 1 pixel, $\theta_{\rm pix} = \theta_{\rm see}/p$ in arcseconds;
- given the size of the detector pixels, derive the plate scale at the detector from $(ps)_{\rm det} = \theta_{\rm pix}/d_{\rm pix}$;
- the required magnification (m) is then

$$m = \frac{(ps)_{\rm tel}}{(ps)_{\rm det}} \tag{5.3}$$

where $m = f_{\rm cam}/f_{\rm coll}$ as before.

m > 1: magnifier, m<1 (usual) focal reducer

5.1.3 Pixel sampling and matching to the plate scale

pixel size and f-number of the focal reducer optics ("camera")

$$\theta_{\rm pix} = 206{,}265 \frac{d_{\rm pix}}{D_{\rm tel}(f/{\rm number})_{\rm cam}}$$

$$\text{where } (f/\text{number})_{\rm cam} = f_{\rm cam}/D_{\rm cam} = F_{\rm cam}.$$

$$(ps)_{\rm tel} = \frac{206{,}265}{f_{\rm tel}} \qquad f_{\rm tel} = D_{\rm tel} \times F \qquad \theta = (ps)_{\rm tel} d_{\rm pix}$$

5.1.3 Pixel sampling and matching to the plate scale

example (Keck, d_pix = 27 um, D_tel = 10 m)

θ_{pix} = 0.56" / F_cam

$$\theta_{\text{pix}} = 206{,}265 \frac{d_{\text{pix}}}{D_{\text{tel}}(f/\text{number})_{\text{cam}}}$$

D_tel /mm

1. Seeing diameter: 0.5" (Mauna Kea)

2. pixel sampling: 2 pix (Nyquist)

3. θ_{pix} = (seeing diameter) / (sampling factor) = 0.5" / 2 = 0.25"
   → F_cam = 0.56 / 0.25 = 2.2

If d_pix = 18.5 um → need f/1.5 camara

CCD pixels get smaller / mirror get larger
→ f/number becomes smaller /faster
→ challenging to invent an optical reimaging system
→ oversampling / smaller image size

5.1.3 Pixel sampling and matching to the plate scale

diffraction limit

$$\theta = 1.22 \frac{\lambda}{D_{\text{tel}}} \text{ radians}$$

λ = 0.5 um, D = 0.5 m → θ = 0.25''
λ = 0.5 um, D = 10 m → θ = 0.0125''

seeing disk: r0 at 0.5 um → at least 0.5''

diameter of diffraction-limited image from f/15 telescope

$$r_{\text{diff}} = 1.22\lambda(f/\text{number})_{\text{tel}}$$

2.44 x 15 = 36.6 um at λ = 1 um

the physical size of the image spot in a camera system

5.1.3 Pixel sampling and matching to the plate scale

For spectrometer

pixel size to the spectral resolution

spectral resolution is partially determined by slit width

sometimes narrower than seeing disk

gather all light w/o loss of spectral resolution

→ Large instrument / oversample the spectral resolution with 2,3 or more pix