Observational Astronomy

SPECTROSCOPY
and
spectrometers

Kitchin, pp. 310-370

Spectroscopic methods

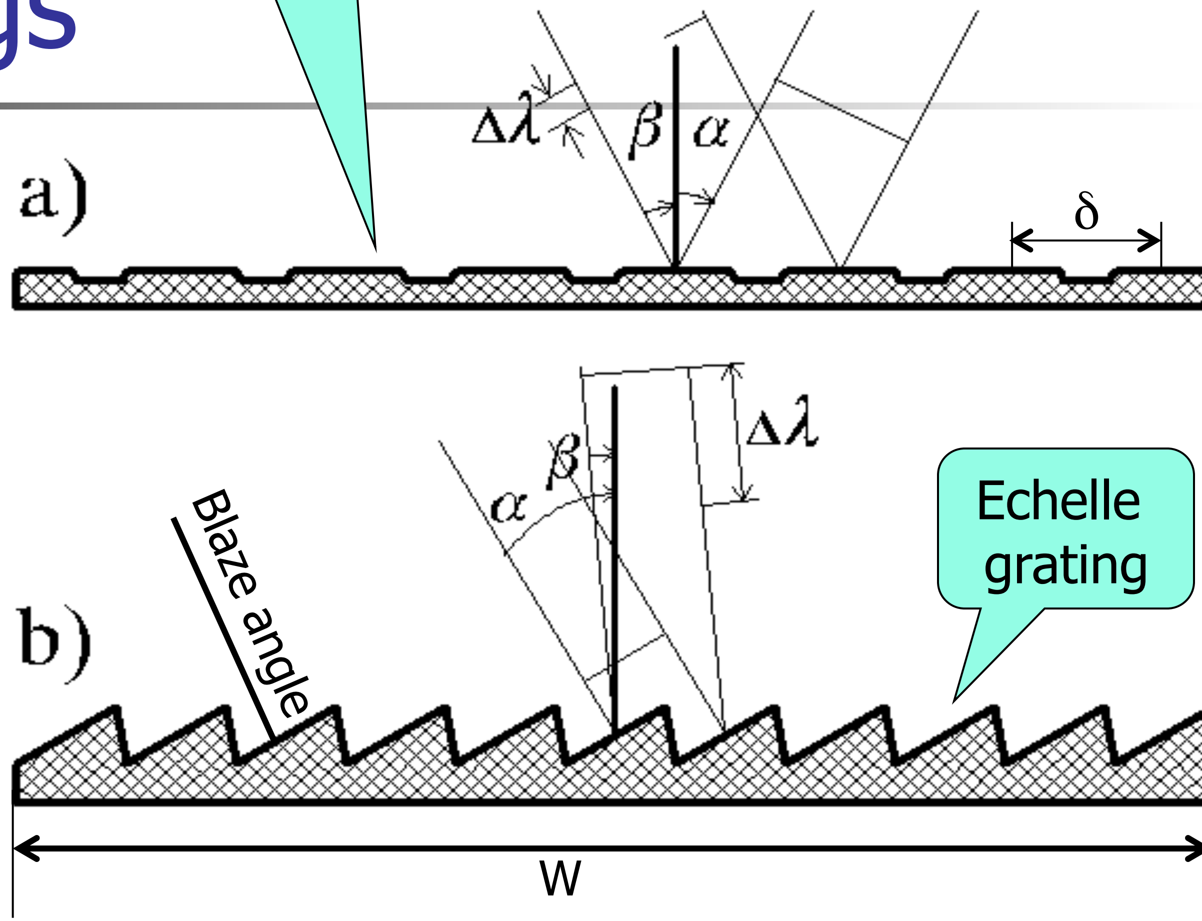
- Different purposes require different instruments
- Main spectroscopic methods:
  - *Spectrophotometry*
  - *Low resolution*
  - *Long slit, high resolution*
  - *High resolution*
- Spectroscopic observations are characterized by: *dispersion/spectral resolution* and *spectral range*

Spectrophotometry

- Typical goal: search for objects with specific spectral features
- Method 1: objective prism, telescope "sees" the source through a prism, therefore each point source looks like a small spectrum
- Method 2: narrow band filters for given spectral features. Often such filters have the possibility to change central wavelength by changing temperature/pressure. There is no slit!

Gratings

Interference:



Grating formula: $\mathrm{OPD} = \delta \sin\alpha + \delta \sin\beta = m\lambda$

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A bit of math:

- Expression for angular dispersion is found by differentiating the grating eq.:

$$m d\lambda = \delta \cos\beta \, d\beta$$

$$\frac{d\lambda}{d\beta} = \delta \cos\beta / m$$ Angular dispersion

- Linear dispersion is readily obtained for a given focal length

$$\frac{d\lambda}{dx} = \delta \frac{\cos\beta}{m \cdot f_{\mathrm{cam}}}$$ Linear dispersion

… and some more …

- Angular resolution. Think of a grating as a mirror, its diffraction angle is given by:

$$\Delta\beta = \lambda / (W \cdot \cos\beta)$$

Projected size of the grating

- … and combining it with the angular dispersion equation:

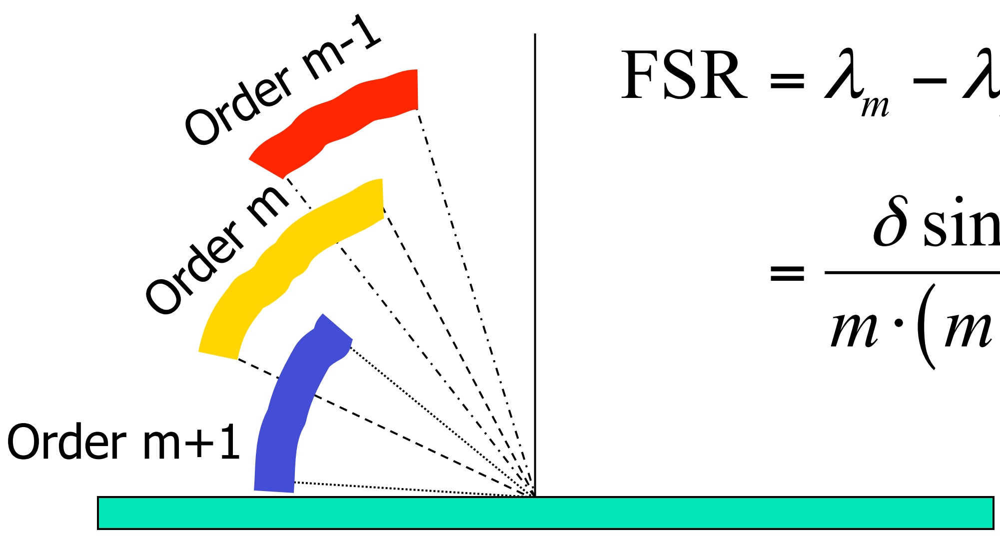
$$\frac{\lambda}{\Delta\lambda} \equiv R = m \cdot \frac{W}{\delta} = m \cdot N$$

?

- *Resolving power depends in the number of illuminated grooves!*

Free spectral range

The free spectral range (FSR) of a diffraction grating is defined as the spectral interval in a given order which does not overlap with the wavelengths in adjacent orders.

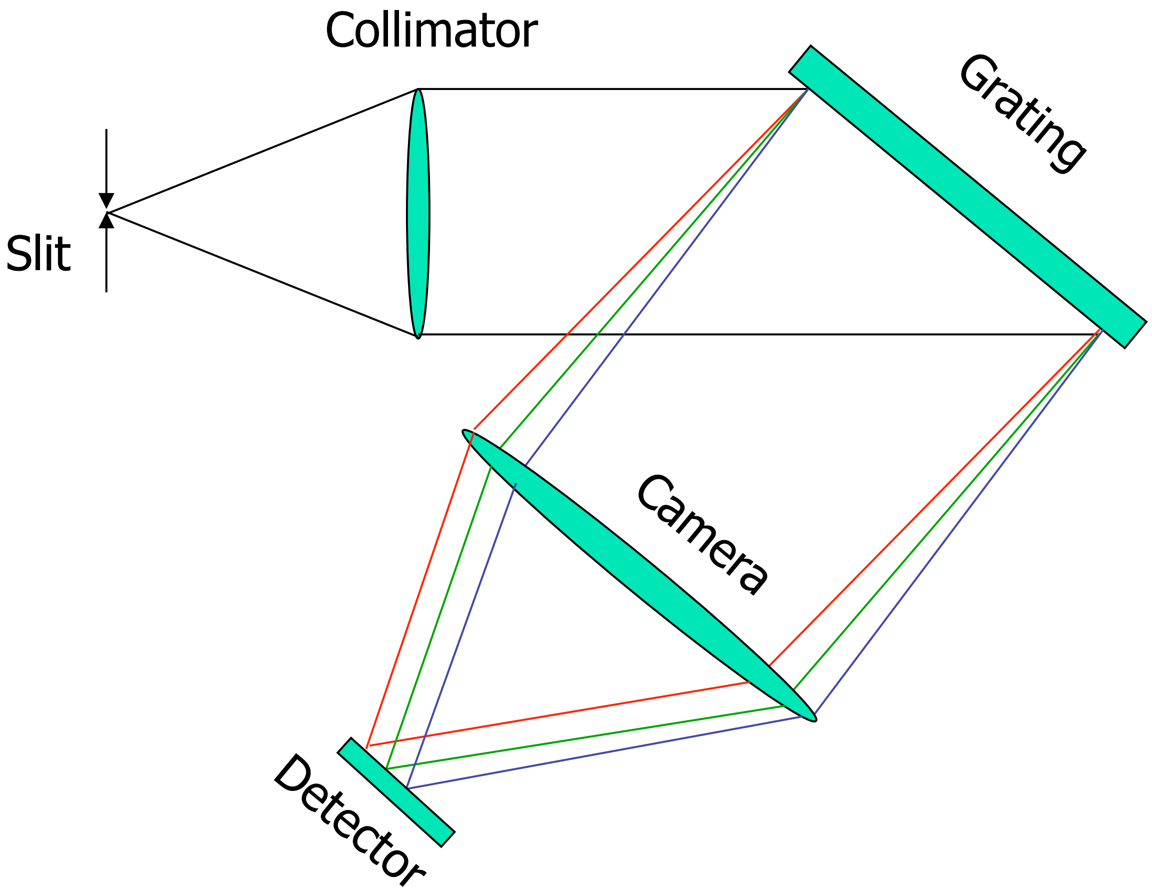


$$\mathrm{FSR} = \lambda_m - \lambda_{m+1} = \frac{\delta \sin\beta}{m} - \frac{\delta \sin\beta}{m+1} =$$

$$= \frac{\delta \sin\beta}{m \cdot (m+1)}$$

For a prism FSR is the whole sp. range!

Grating spectrometers



Real world: the seeing and the pixel size

- The angular slit size as seen by the grating is:

$$\Delta\alpha = s / f_{\mathrm{coll}}$$

where f_{coll} is the focal length of the collimator and s is the linear width of the slit. Grating equation connects this to the angular resolution element:

$$\Delta\alpha \cos\alpha = s / f_{\mathrm{coll}} \cos\alpha = -\Delta\beta \cos\beta$$

$$\left|\Delta\beta\right| = \frac{s \cdot \cos\alpha}{f_{\mathrm{coll}} \cdot \cos\beta}$$

- If we try to match this to the angular resolution of the grating we end up with too narrow slit.
- In practice, we select the slit, translate this to angular resolution and select the camera focal length to match the pixel scale.

Putting some numbers

Home work

The spectrograph for the BWT is based on a 20 cm grating with a blaze angle of 66.5º and 72 grooves per mm

- Find angular resolution of the grating at 4000 Å, 6000 Å and 8000 Å
- Find optimal slit size with collimator length of 80cm
- Take a realistic seeing (2”) and the corresponding entrance slit size. Compute the resolution R and the camera focal length to achieve 3 pixel sampling of a resolution element (15 micron pixel size)
- Why is it hard to make high-resolution spectrometers for large telescopes? How the size of the primary mirror affects parameters and dimensions of a spectrometer?

Modern concept

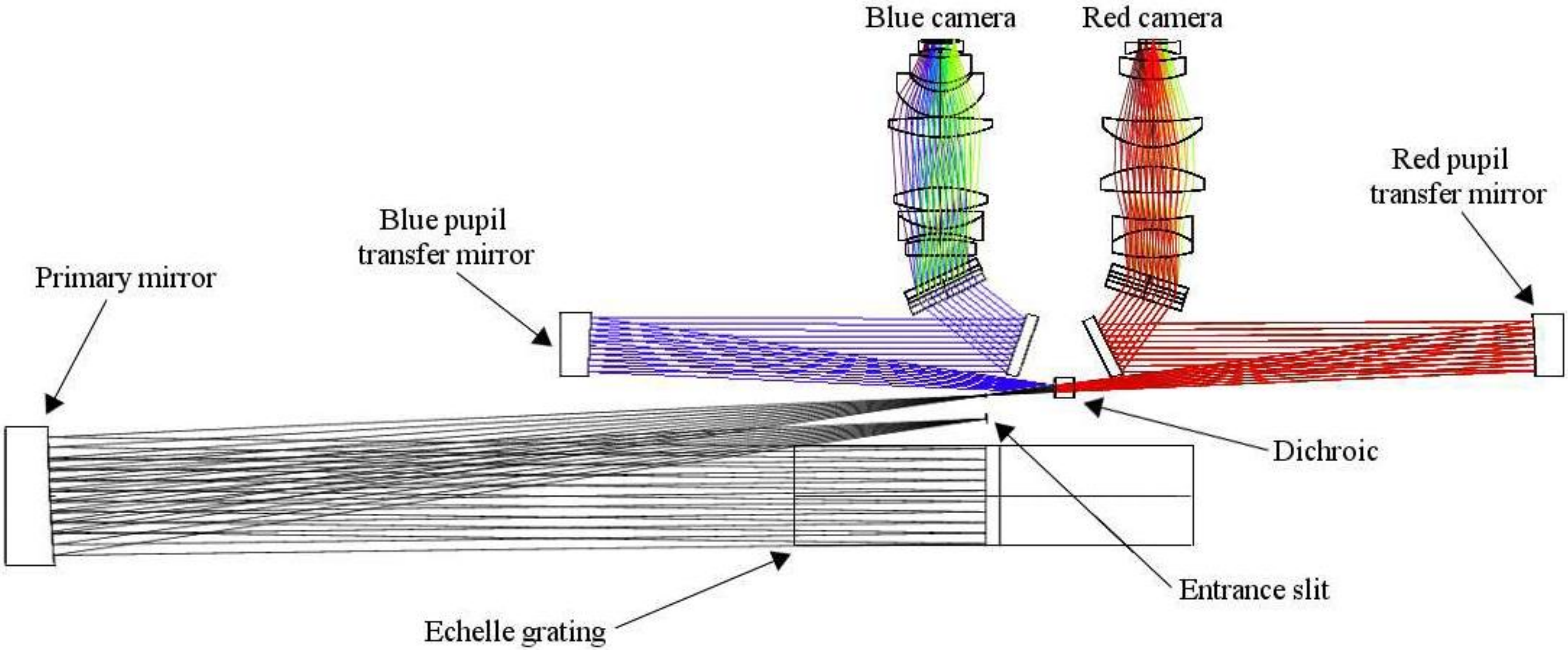
- Echelle gives high resolving power (high orders) and high efficiency (no dark stripes)
- Spectral orders overlap (maximum reflection at blaze angle) $\Rightarrow$ order selection or cross-disperser is needed (e.g. grating or prism)
- Central wavelength of order m is given by:

$$\lambda_m = 2\delta \sin\theta_{\text{blaze}} / m$$

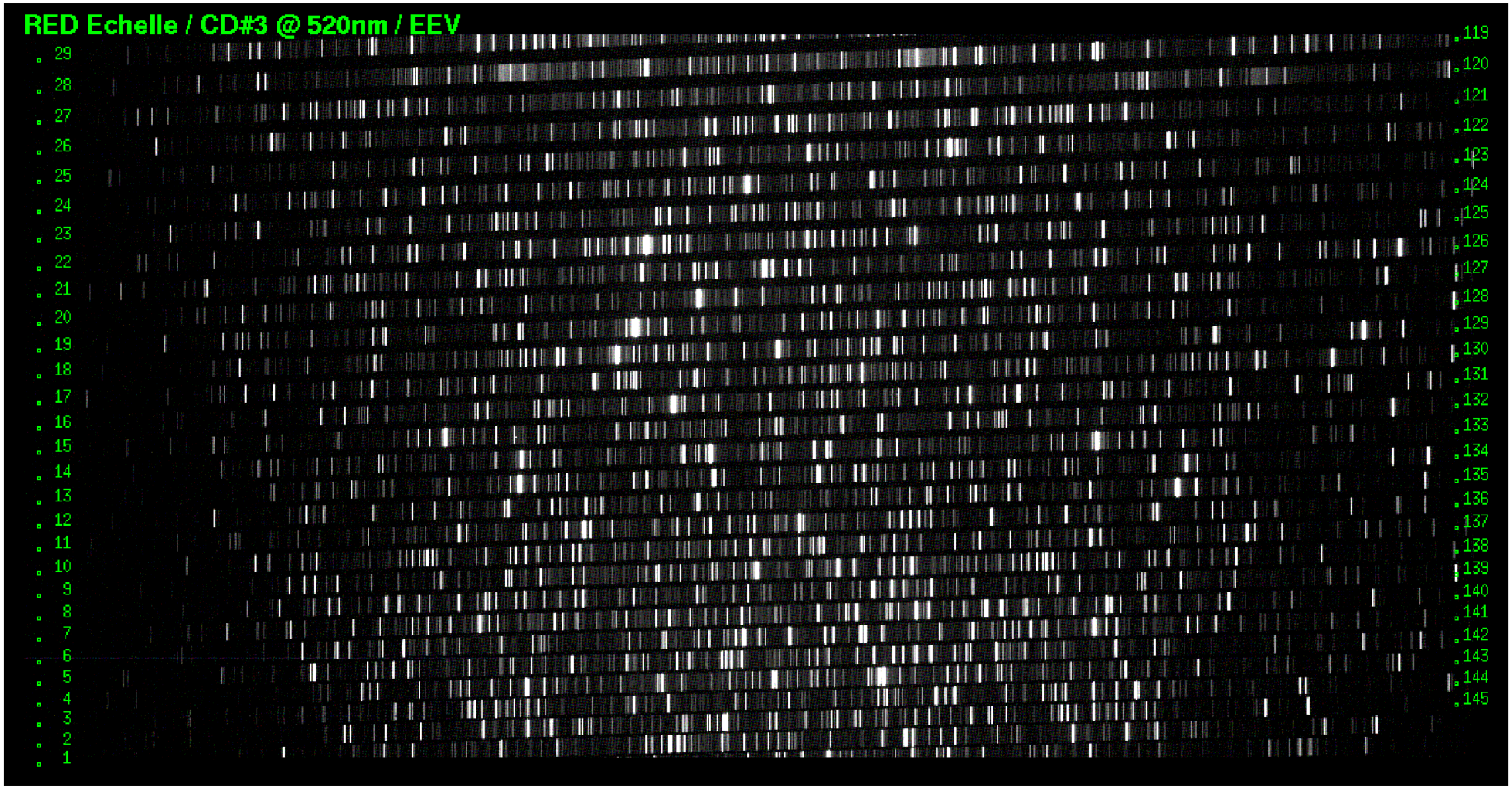
- With a cross-disperser the whole spectrum is packed in a rectangular 2D format, perfect for an electronic detector

Spectrograph designs

Echelle, white pupil (e.g. SALT-HRS)



Echelle focal plane layout

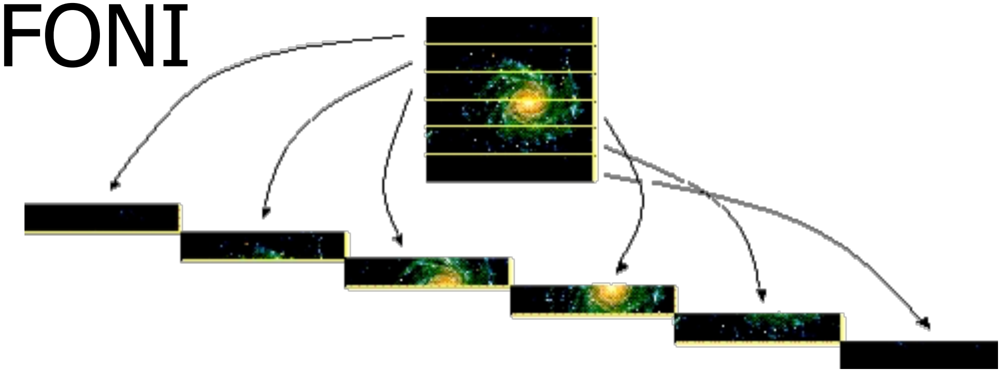


Side effects

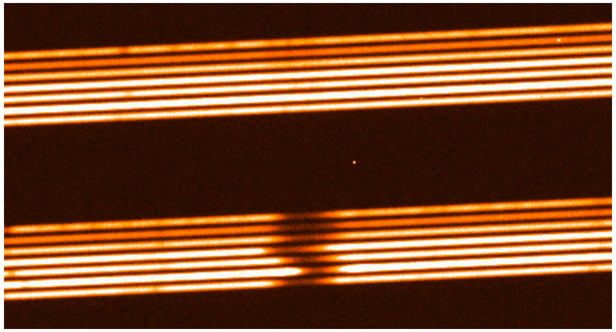
- Orders are curved
- Order spacing changes
- Short FSR
- Camera aberrations directly affect resolution
- Hard to reproduce detector fringing

Spatial information in spectroscopic instruments

- IFU instruments
  2D image slices are re-arranged in 1D slit. E.g. SINFONI



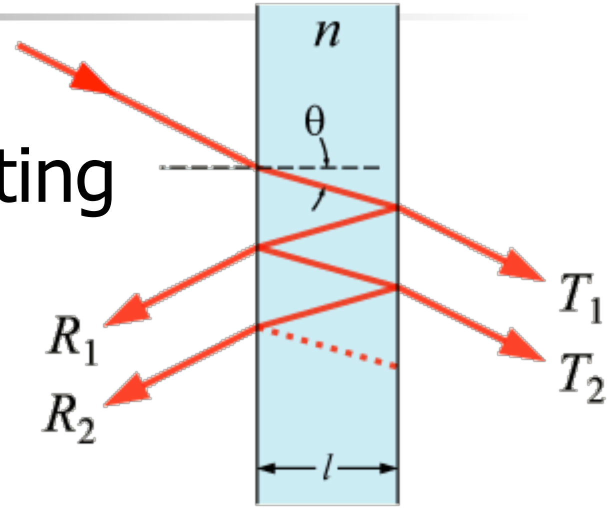
- Multi-object instruments.
  E.g. FORS, FLAMES

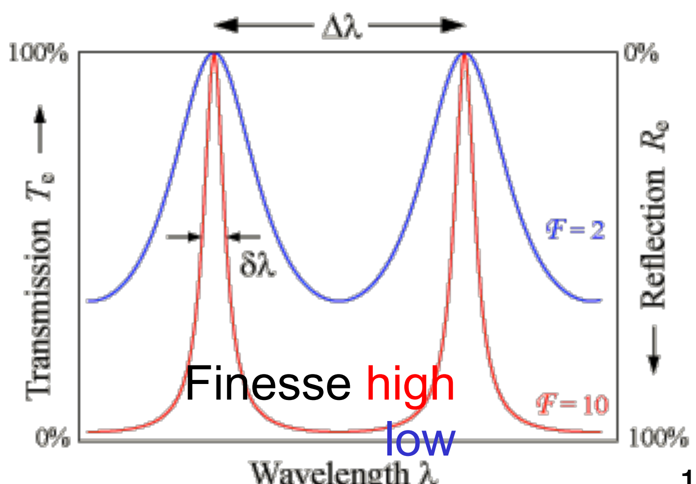


http://www.physik.uni-osnabrueck.de/kbetzler/sos/fabryperot.pdf

Fabry-Perot interferometer

- The resolution is determined in the same way as for a grating
- Transmission/Reflection ratio depends on the wavelength
- The ratio between the reflection and the transmission peaks is called *finesse*
- F-P is often used as tunable filter



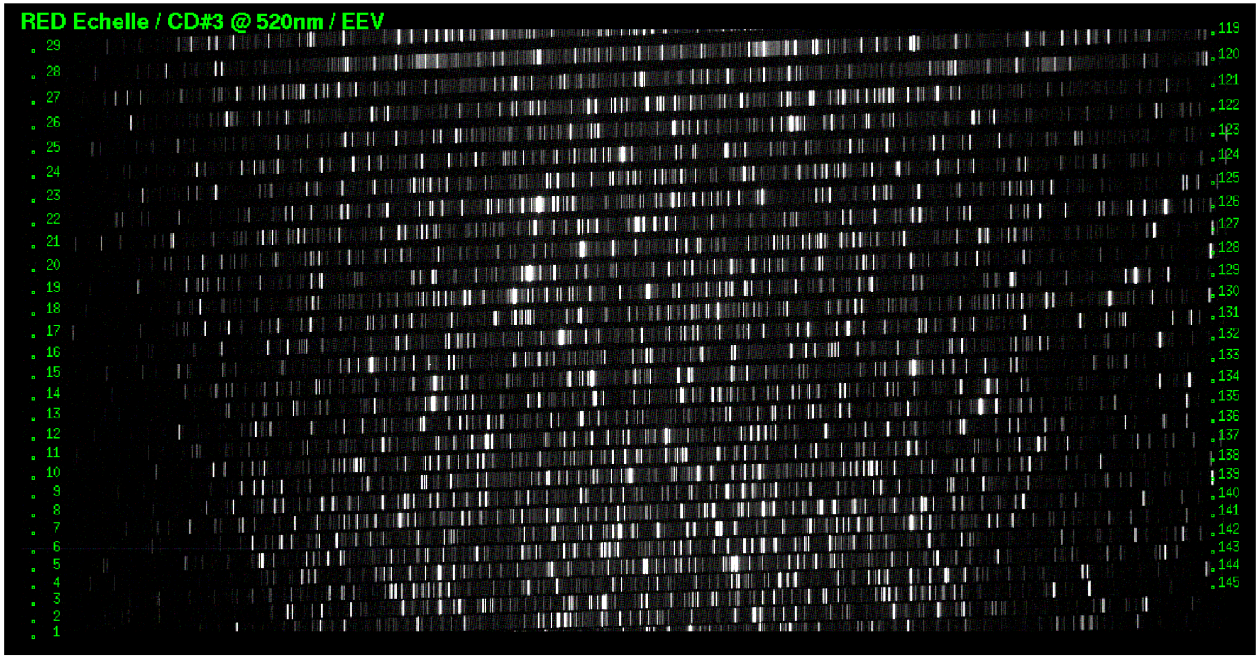


Spectroscopy-specific calibrations

- Spectral order tracing
  Narrow flat through spectrometer
- Wavelength scale (PSF)
  Emission line lamp, FP or laser comb
- Dispersed flat fields
  Continuum lamp emulating the telescope beam through spectrometer
- Special calibrations
  Absorption gas cell or simultaneous wavelength reference

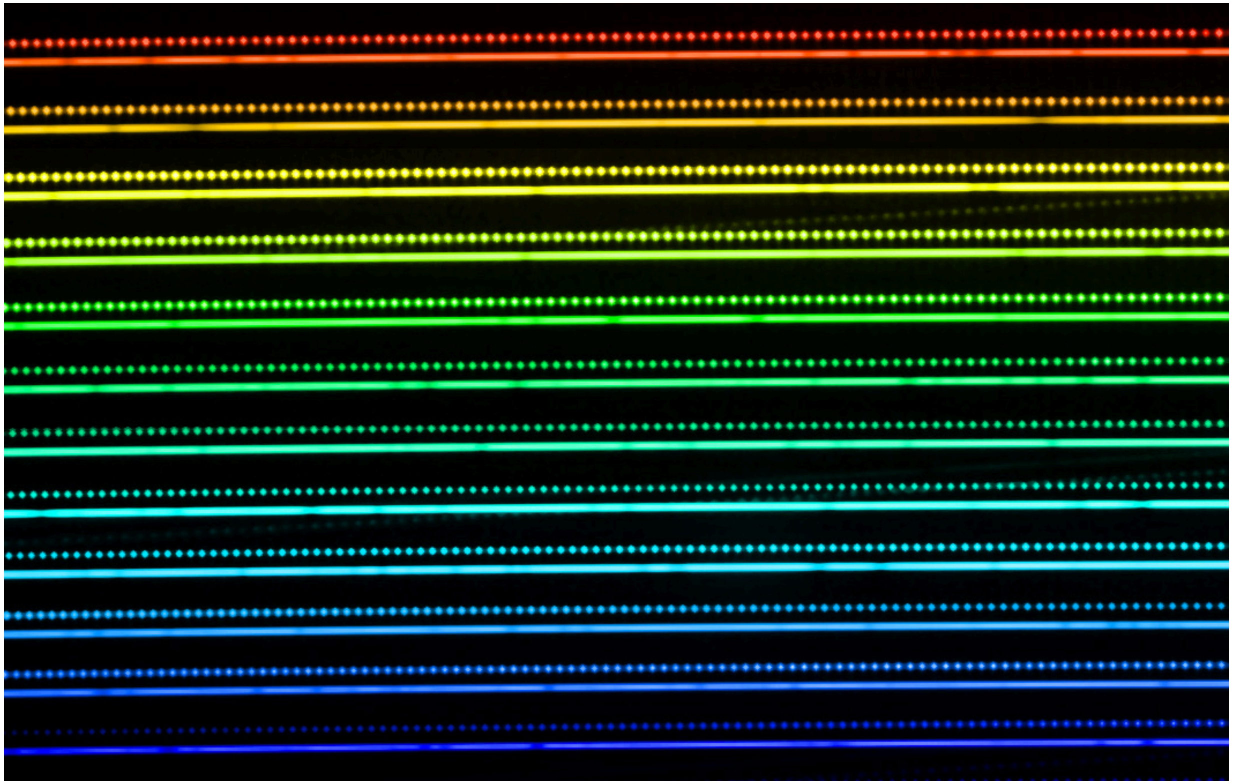
Wavelength calibrations

- Hollow cathode lamps (ThAr, UNe etc.)



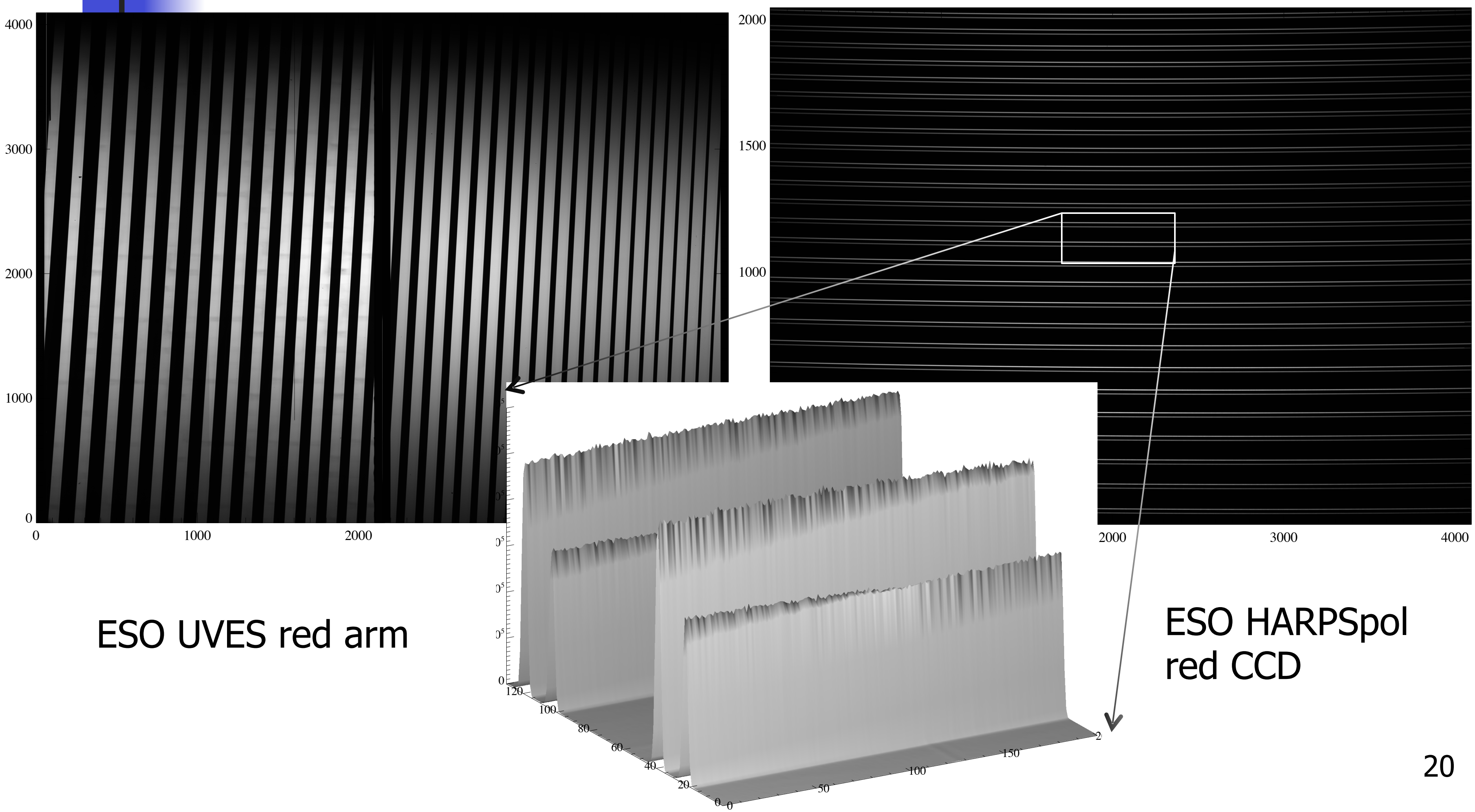
Wavelength calibrations

- Fabry-Perot and laser comb (fixed frequency spacing and width)



Notice any problem here?

Dispersed flat field

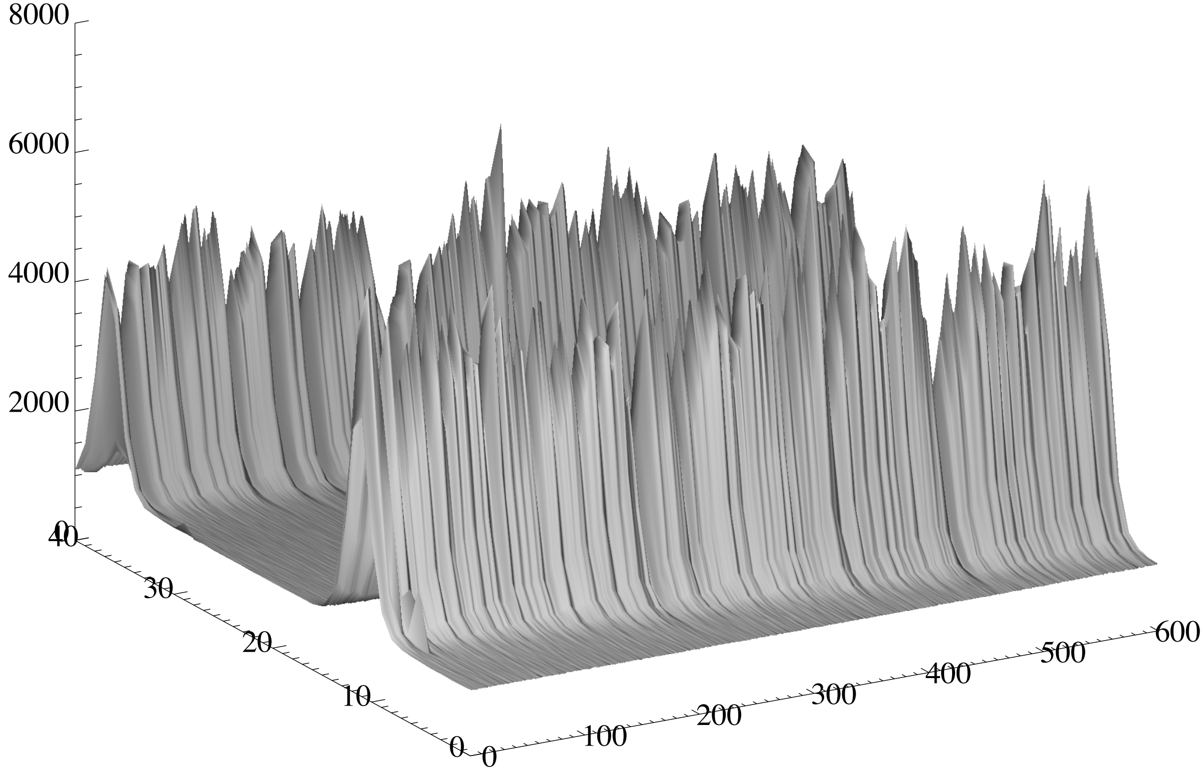


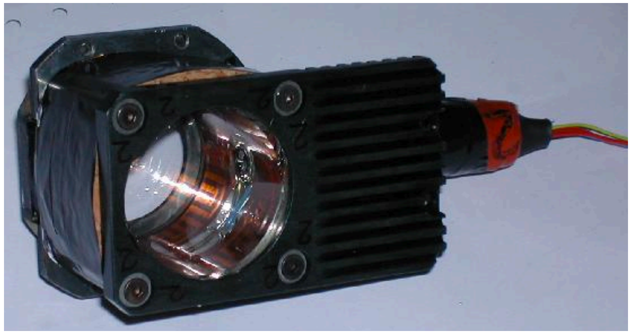
ESO UVES red arm

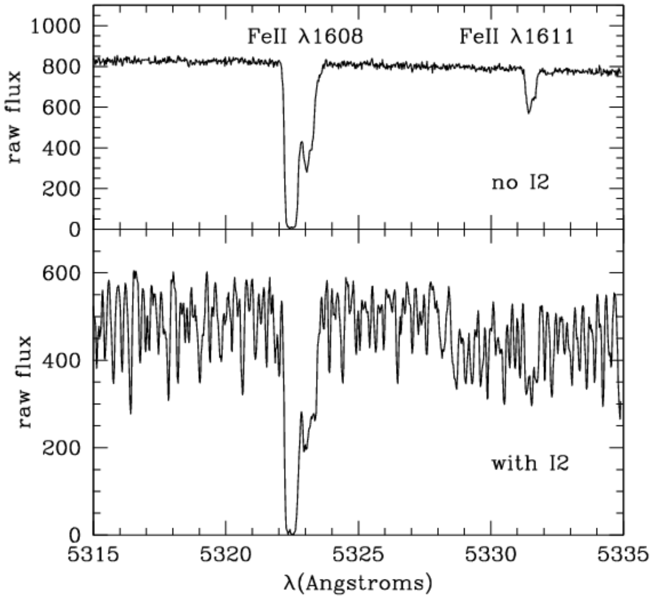
ESO HARPSpol red CCD

Simultaneous calibrations

- Iodine gas cell







Next time

Spectroscopic data reduction