Astro 500

Techniques of Modern Observational Astrophysics

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Lecture Outline

Spectroscopy from a 3D Perspective

- ✓ Basics of spectroscopy and spectrographs
- ✓ Fundamental challenges of sampling the data cube
- Approaches and example of available instruments
  - I: Grating-dispersed spectrographs
    - Echelles
    - Bench Spectrograph (WIYN 3.5m)
    - Robert Stobie Spectrograph (SALT 11m)
  - II: Fabry-Perot interferometry
  - III: Spatial heterodyne spectroscopy

Approaches

Examples of available instruments

- Interferometry-I: Fabry-Perot imaging
  - the bull's eye: implications for design and use
  - sky stability: calibration design
- Interferometry-II: Spatial-heterodyne spectroscopy
  - low-cost, diffraction-limited high-resolution capability
  - multi-plex disadvantage: implications for design and use

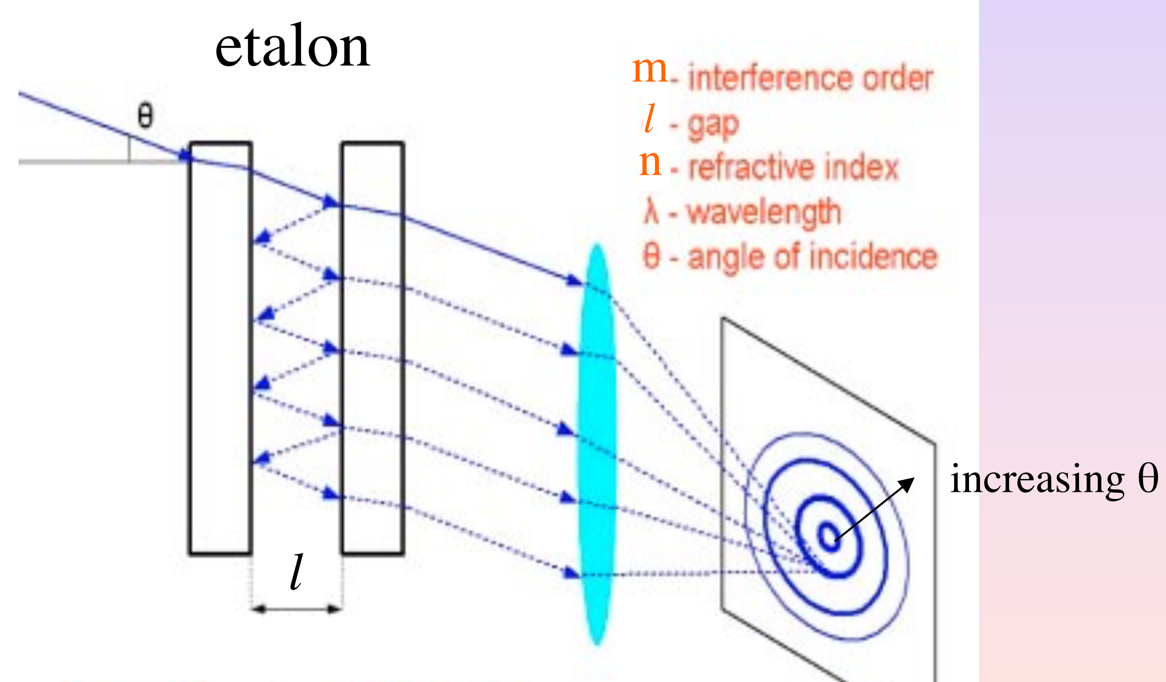
Fabry-Perot

- A type of interferometer

• *Remember*: angles in a collimated beam correspond to different field points at a focus.

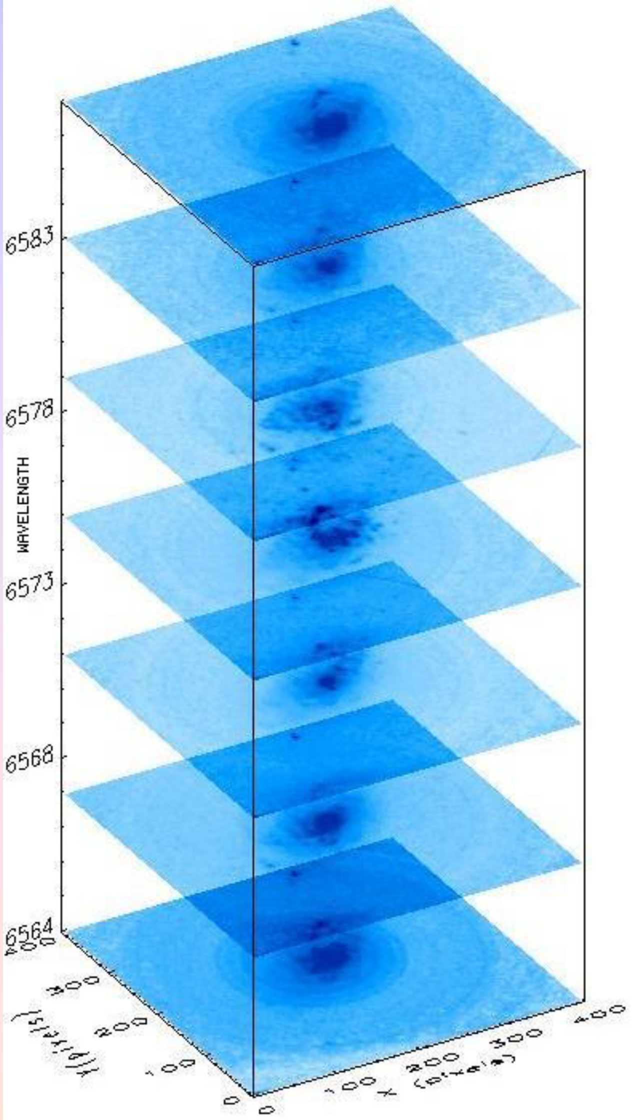
• So what happens if the etalon is not in a collimated beam?

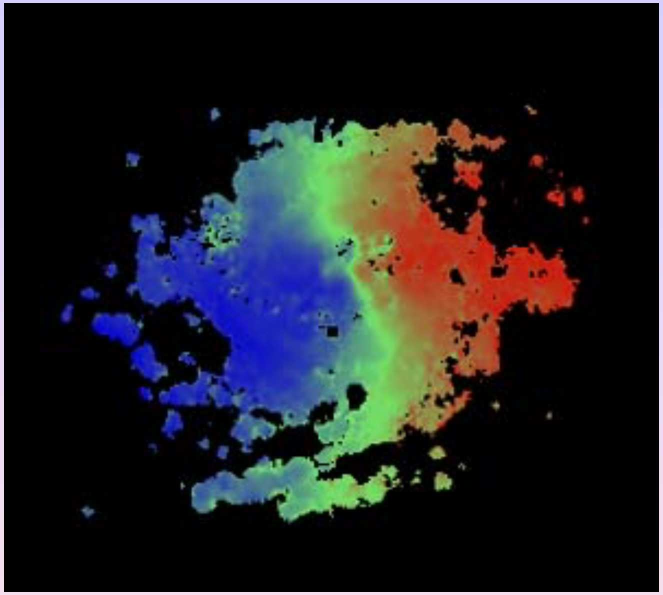
What about the apex angle of the diverging/converging beams?



$$m\lambda = 2\, l\, n \cos\theta$$

F-P data cube for an imaging system





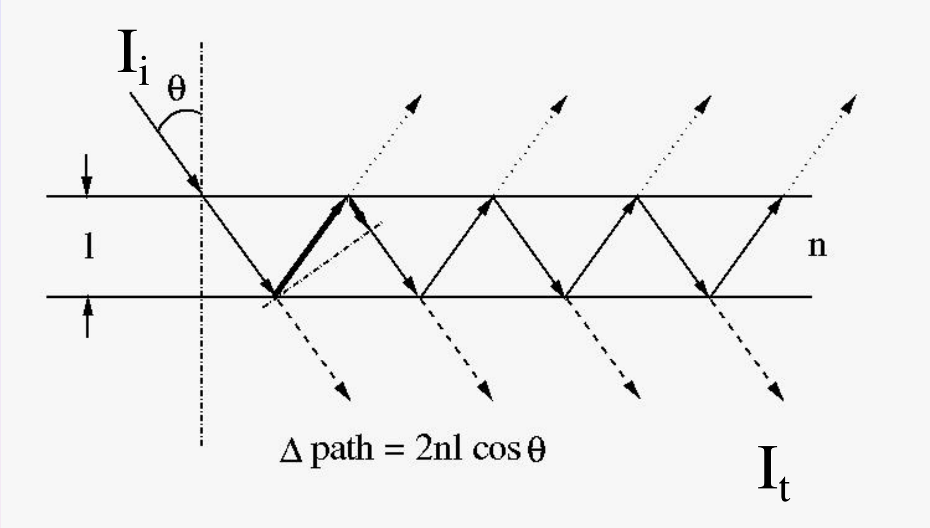
Color-coded velocity map

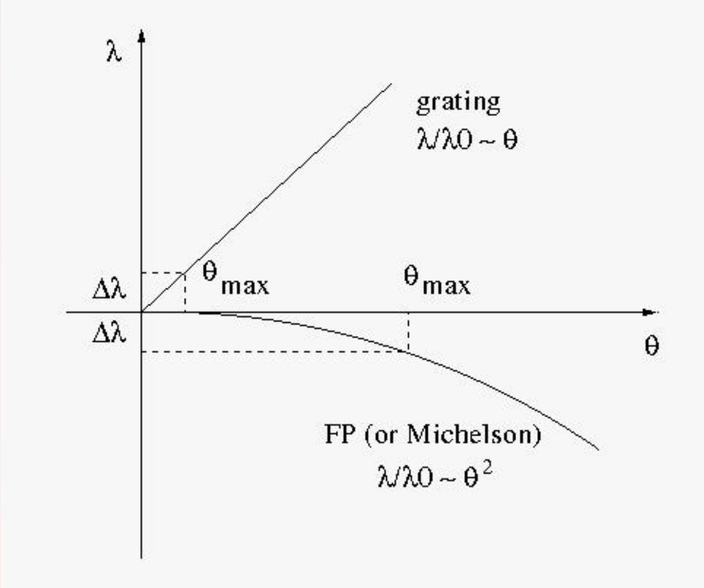
But in reality each “snap-shot” with etalon-gap d is only monochromatic at a given field point from the optical axis, i.e., the observed data-cube is curved and has to be wavelength-rectified.

Interferometry-I: Fabry-Perot imaging

Basics

- **Etalons** (flat glass plates) are spaced by some distance *l*, filled with gas of refractive index *n*, and coated to have high reflectivity.
- Light incident at some angle, θ, produces internal reflections, with transmission when Δpath yields positive interference.





- **I_t/I_i** given by Airy function with peaks $I_t = I_i$ when

  Δpath = mλ, or

  $\lambda_\theta = (2nl\,/m) \cos\theta$

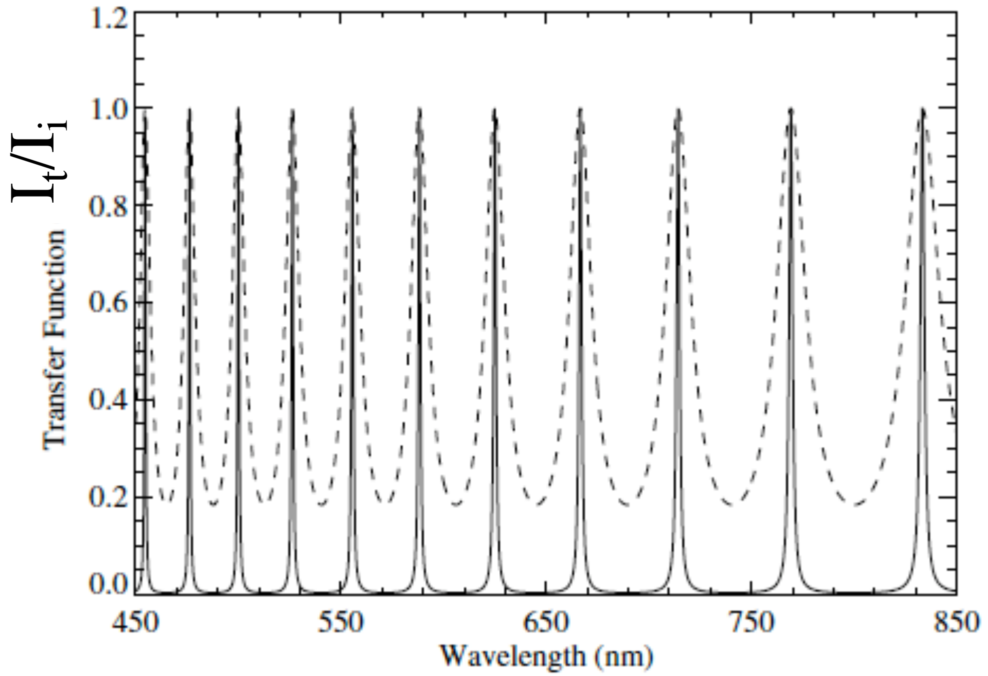
  $= \lambda_0 \cos\theta$

- Compare to grating equation:

  $\lambda = (2\,\sigma/m)\ \sin\theta$ (Littrow)

➢ ***FP is field-widened for same spectral resolution***

Interferometry-I: Fabry-Perot imaging
Transmission



Airy function transmission profiles with $l = 5$ μm and coatings with reflectivity $\mathcal{R}$ of 0.8 (solid) and 0.45 (dashed)

$$I_t = I_i \frac{T^2}{(1-R)^2} \frac{1}{1 + F\sin^2(\Delta/2)}$$

$$\Delta = 4\pi l \cos\theta/\lambda$$

$$\mathcal{F} = 4\mathcal{R}(1-\mathcal{R})^2$$

Finesse (bien sur)

(here just the reflective finesse)

Interferometry-I: Fabry-Perot imaging

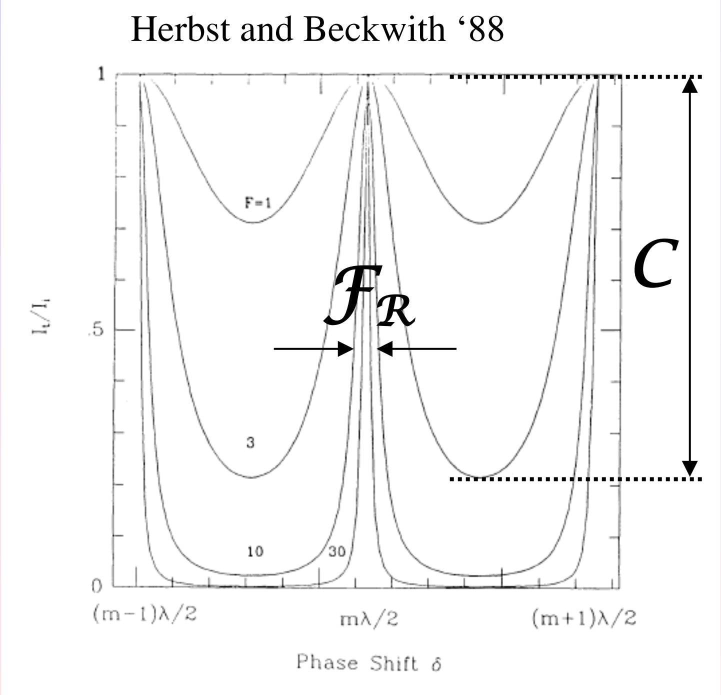
Useful relations

- **Tune** gap (l) or pressure (index n) to control/scan central wavelength
  - $\lambda_\theta = (2nl / m) \cos\theta$
- **Q** = free spectral range
  $= \lambda^2 / 2\,l \sim 1 / 2n\,l \cos\theta$
  - order blocking filters are needed
- **R** $= \lambda / d\lambda = 2\,l\,\mathcal{F}_\mathcal{R} / \lambda = m\,\mathcal{F}_\mathcal{R}$

spectral resolution

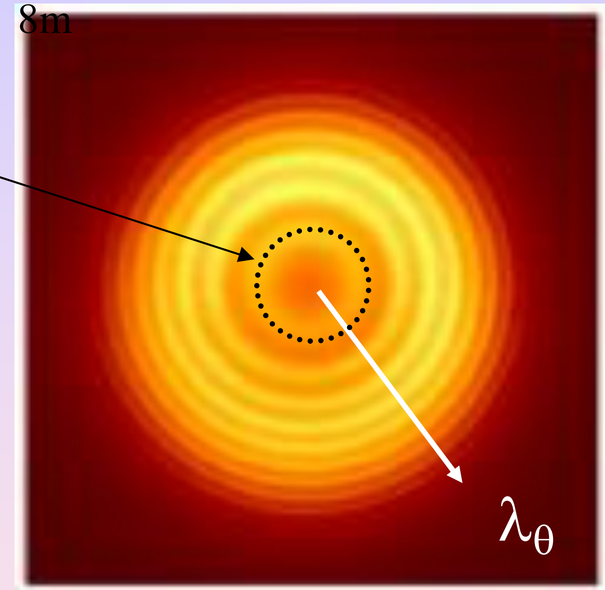
reflectivity

- $\mathcal{F}_\mathcal{R}$ = reflective finesse $= \pi\,\mathcal{R}^{1/2} / (1 - \mathcal{R})$
  - ~ number of back/forth reflections; typical values of 20 to 30 in astro. apps.
  - R ~ total path difference divided by λ.
  - High resolution requires: large gaps and high finesse.
- ***C* = Contrast** $= I_{max} / I_{min} = (1+\mathcal{R})^2/(1-\mathcal{R})^2 = 1 + 4(\mathcal{F}_\mathcal{R}/\pi)^2$



Interferometry-I: Fabry-Perot imaging
Bull's eye (Jaquinot spot) and rings

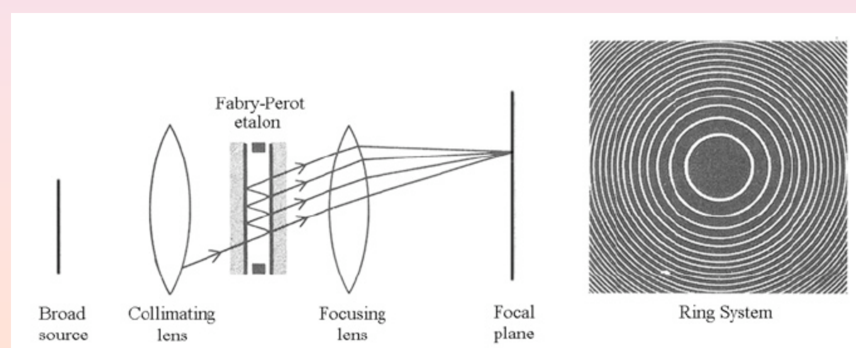
Hartung et al.'04 NACO, VLT 8m



- **The bull's eye:**
  - What is θ so that $\lambda_0/|\lambda_0-\lambda_\theta| < R$?
  - $\theta_{max} = (2/R)^{1/2}$
  - This quantity is *independent* of the telescope, and is a property of the etalon.

> Where does this come from?
> What's the angle of the nth ring?
> How does the ring area (within the resolution element) change with n?

- Couple to a telescope to modify angular resolution:
  - $A\Omega$ is conserved
  - $\alpha = \theta\, D_e / D_T$
    - o α = angle on the sky
    - o θ = angle on the etalon
    - o D_e= etalon diameter
    - o D_T = telescope diameter



Interferometry-I: Fabry-Perot imaging

Finesse

Finesse:

(mais oui)

$$\frac{1}{\mathcal{F}^2} = \frac{1}{\mathcal{F}_R^2} + \frac{1}{\mathcal{F}_D^2}.$$

See: Atherton et al. 1981
Opt. Eng. 806, 20

Reflective finesse

Defect finesse:

$$\frac{1}{\mathcal{F}_D^2} = \frac{1}{\mathcal{F}_{\mathrm{Dc}}^2} + \frac{1}{\mathcal{F}_{\mathrm{Dr}}^2} + \frac{1}{\mathcal{F}_{\mathrm{Dp}}^2}.$$

$$\mathcal{F}_{\mathrm{Dc}} = \frac{\lambda}{2\delta t_c}$$

Plate curvature

$$\mathcal{F}_{\mathrm{Dr}} = \frac{\lambda}{4.7\delta t_r}$$

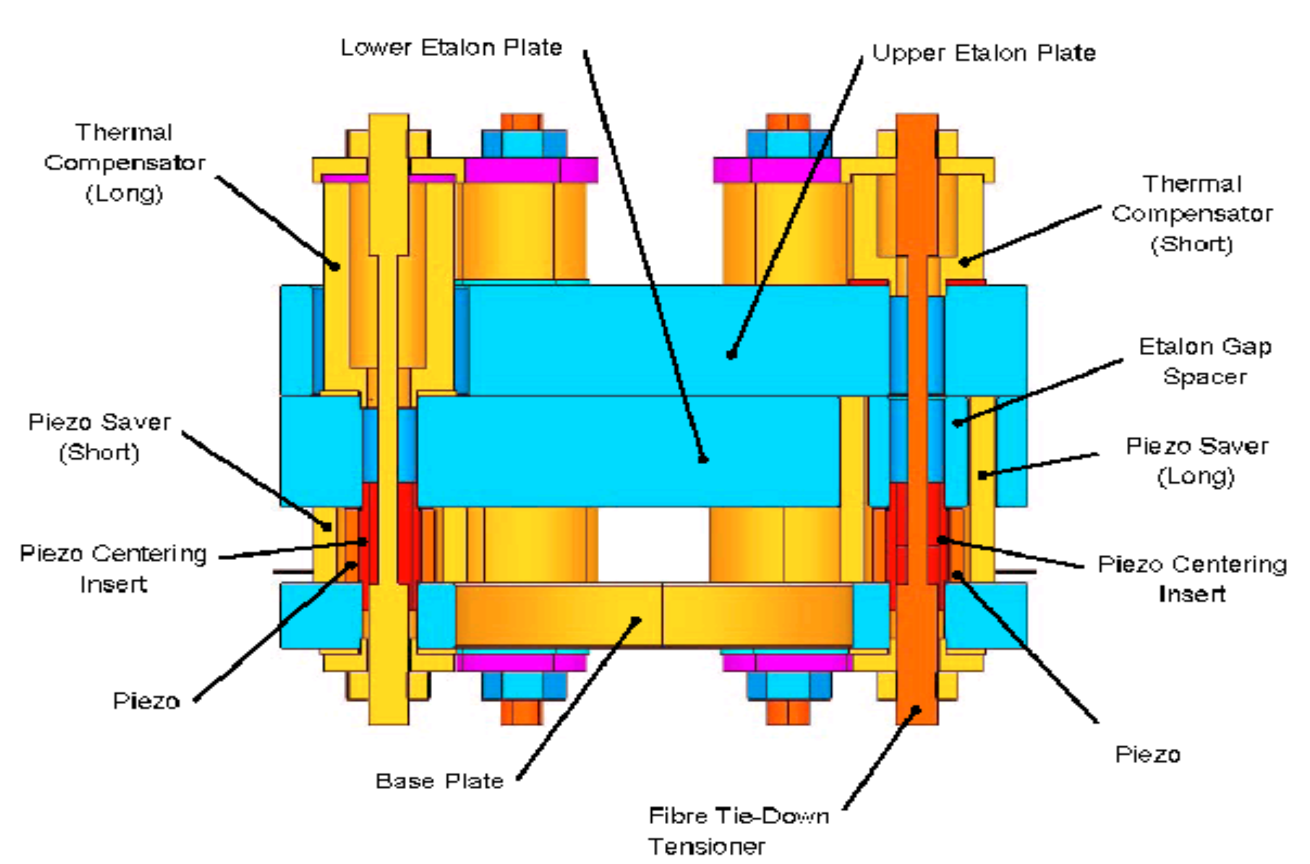
Surface irregularities/roughness

$$\mathcal{F}_{\mathrm{Dp}} = \frac{\lambda}{\sqrt{3}\delta t_p}$$

Departure from parallelism

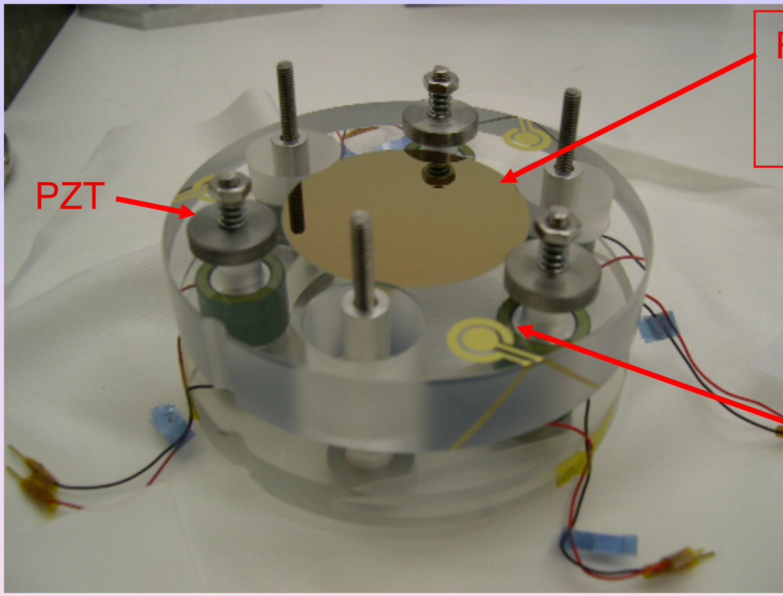
An Example:
JWST Etalon Design

[Courtesy: Bob Abraham and the F2T2 Team]

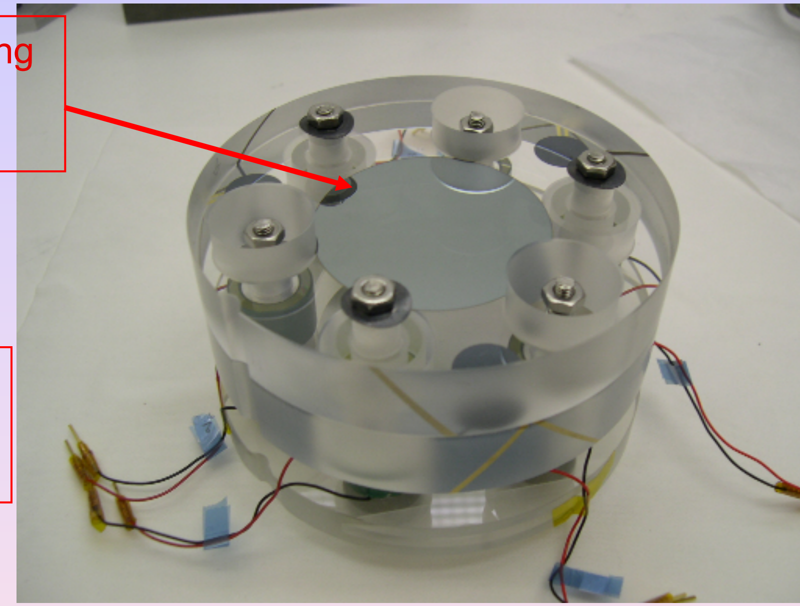


Etalon Prototype

[Courtesy: Bob Abraham and the F2T2 Team]



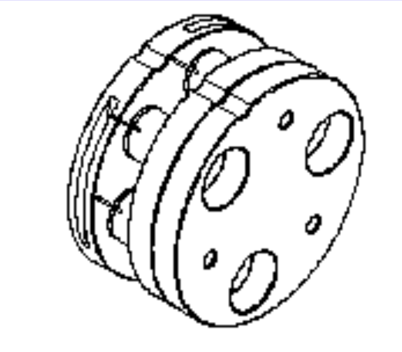
Bottom Plate & Mounting Ring

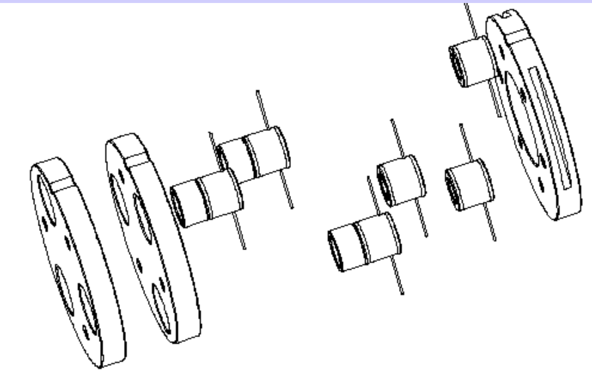


Completed Etalon

- The etalon consists of two 20 mm thick SiO_2 plates with the reflective coating applied in the central ~50 mm
- There are three piezo-electric transducers supporting the bottom plate and three PZTs + spacers supporting the top plate
- Capacitive displacement sensors are used to control the spacing of the etalon plates

JWST Etalon
Basic Design Features





- Etalon plates surface figure better than 11 nm before coating (32 nm after).
  - Meets optical requirement of finesse.
  - Optical materials are silicon for LW etalon and silica for SW.
- 7.5 μm nominal gap parallel over clear aperture.
  - Translates to a 4.5 μm gap between the coatings, because of coating thickness.
  - Nominal gap is set by precise manufacture of spacers made of plate material.
- Gap to be stepped using piezoelectric actuators.
  - Six actuators in total, three for the top plate, three for the bottom.
  - Larger of two available sizes selected for higher bearing area.
- Gap spacing feedback provided by capacitive displacement sensors.

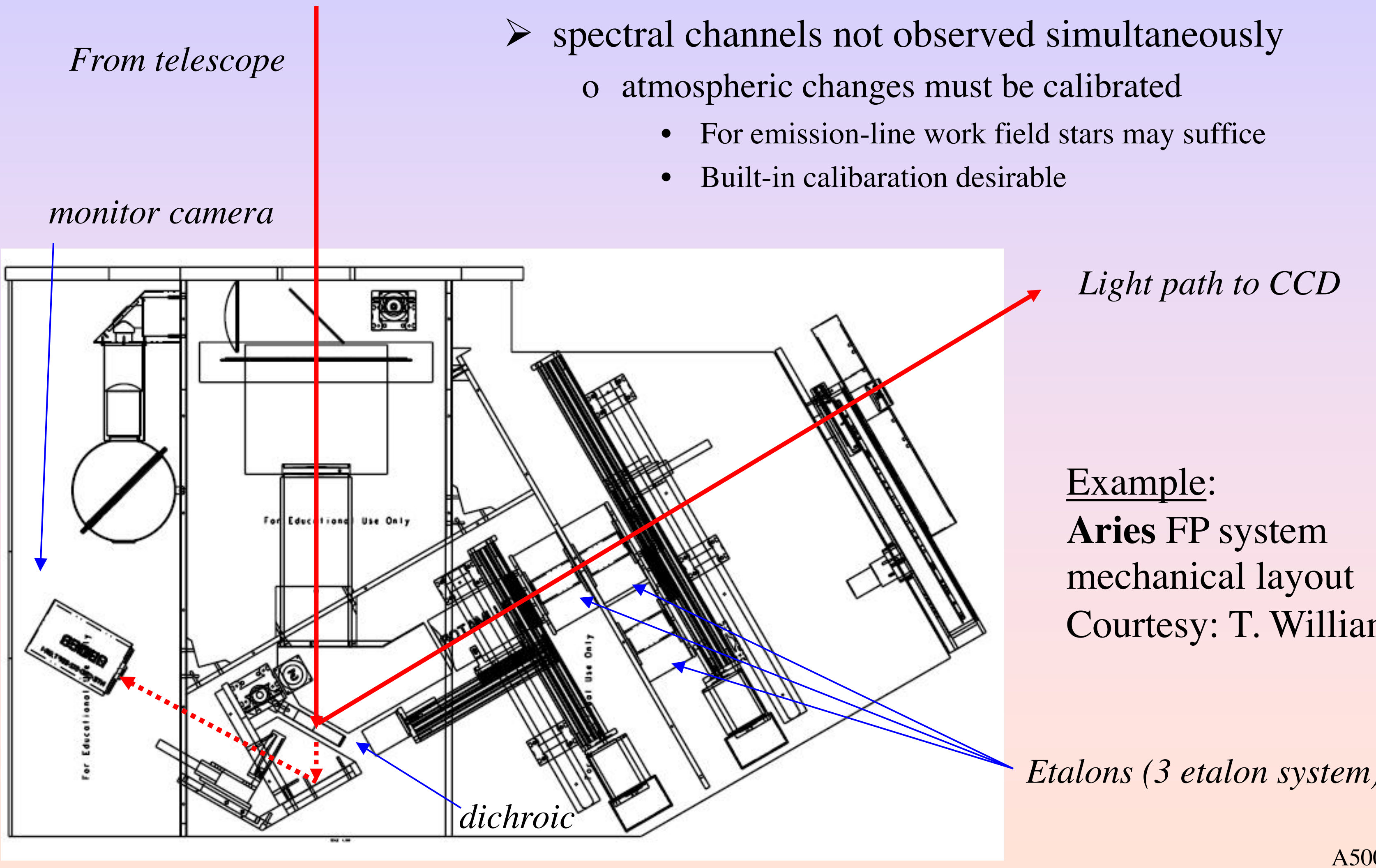
JWST TFI Etalon Requirements

Parameter	Shortwave Etalon	Longwave Etalon	Notes
Wavelength Range	1.2 to 2.1 μm	2.0 to 4.8 μm	Wavelength ranges are not finalized, transition wavelength may be lower
Spectral Resolution	R > 80		Etalon intrinsic resolution higher than requirement on FGS-TF channels.
Clear Aperture	56 mm		Pupil size ~40 mm. Set by etalon location in optical path
Finesse	~30		Compromise between fabrication challenges & minimizing # of blockers
Surface Figure (P-V)	< 30 nm	< 60 nm	Coated etalon surface figure must support reflectance finesse.
Transmittance	> 75%		Will be set primarily by achieved surface figure.
Contrast	> 100		Peak transmittance divided by minimum between spectral peaks
Passband Shift with FOV	< 5%		Ideal air spaced etalon has < 1.2%, typical designs have < 2.5%
Number of Blocking Filters	< 6	< 6	Goal is to minimize filter wheel size and simplify operations.

- The free spectral range is maximized by using a low order: small gap spacing
- A finesse of ~30 and a spectral resolution of R~100 suggest operating in 3rd order.

Interferometry-I: Fabry-Perot imaging
Ground-based instruments

- Sky stability:
  - ➢ spectral channels not observed simultaneously
    - o atmospheric changes must be calibrated
      - For emission-line work field stars may suffice
      - Built-in calibaration desirable



<u>Example</u>:
Aries FP system
mechanical layout
Courtesy: T. Williams

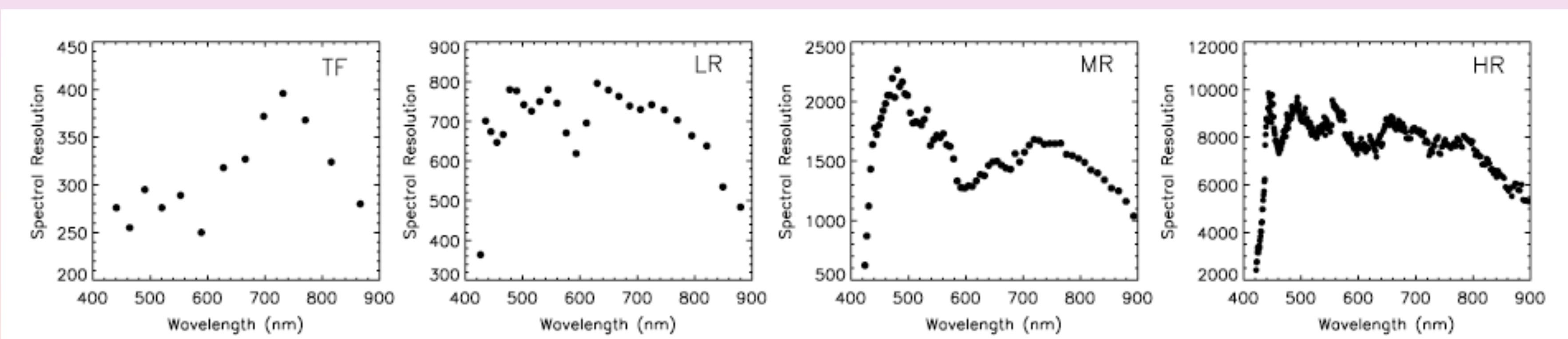
Interferometry-I: Fabry-Perot imaging
Ground-based instruments: RSS

- RSS, SALT 9.2m
  - Imaging FP
  - 150 mm etalons
  - 9200 mm telescope
  - 8 arcmin FoV, 0.2 arcsec sampling
  - R = 300 to 9000 in 4 modes
  - 430-860 nm

3 Etalons: l = 5-11, 27, and 135 μm

$$\mathcal{F}_D \sim 50$$
$$\mathcal{F}_R = 30$$
$$\longrightarrow \quad \mathcal{F} \sim 25$$

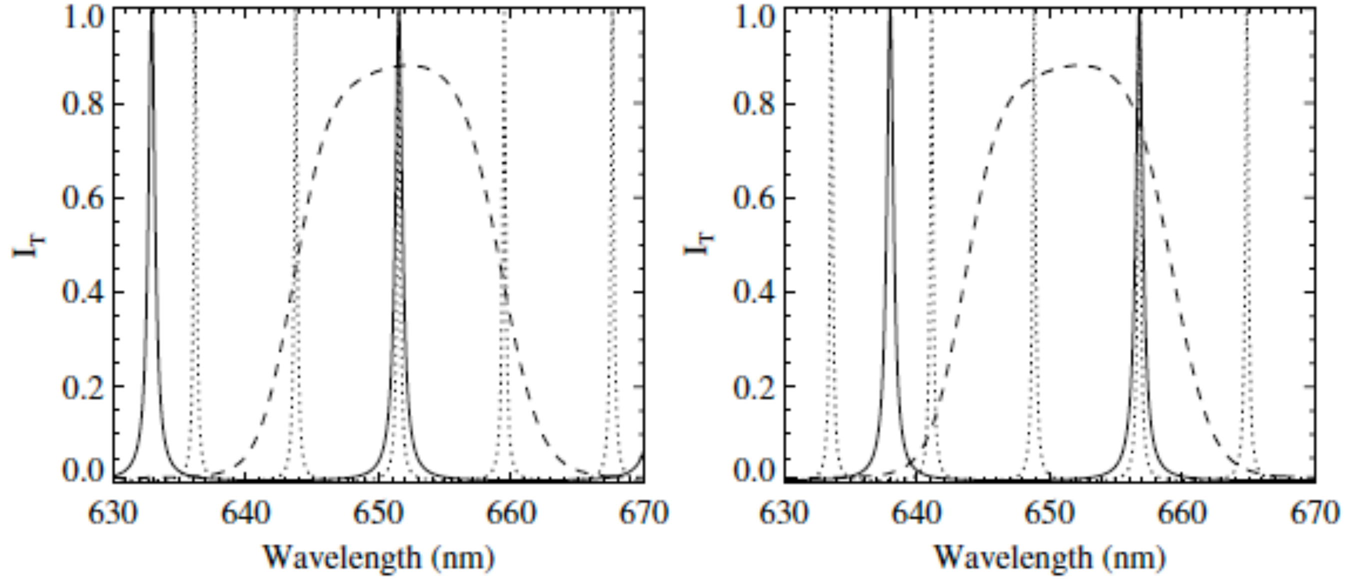
SG etalon l=5-7 μm | SG etalon l=9-11μm | SG+ MG etalon l=22-28μm | SG+ LG etalon l=130-136μm



Rangwala et al. 2008, AJ, 135, 1825

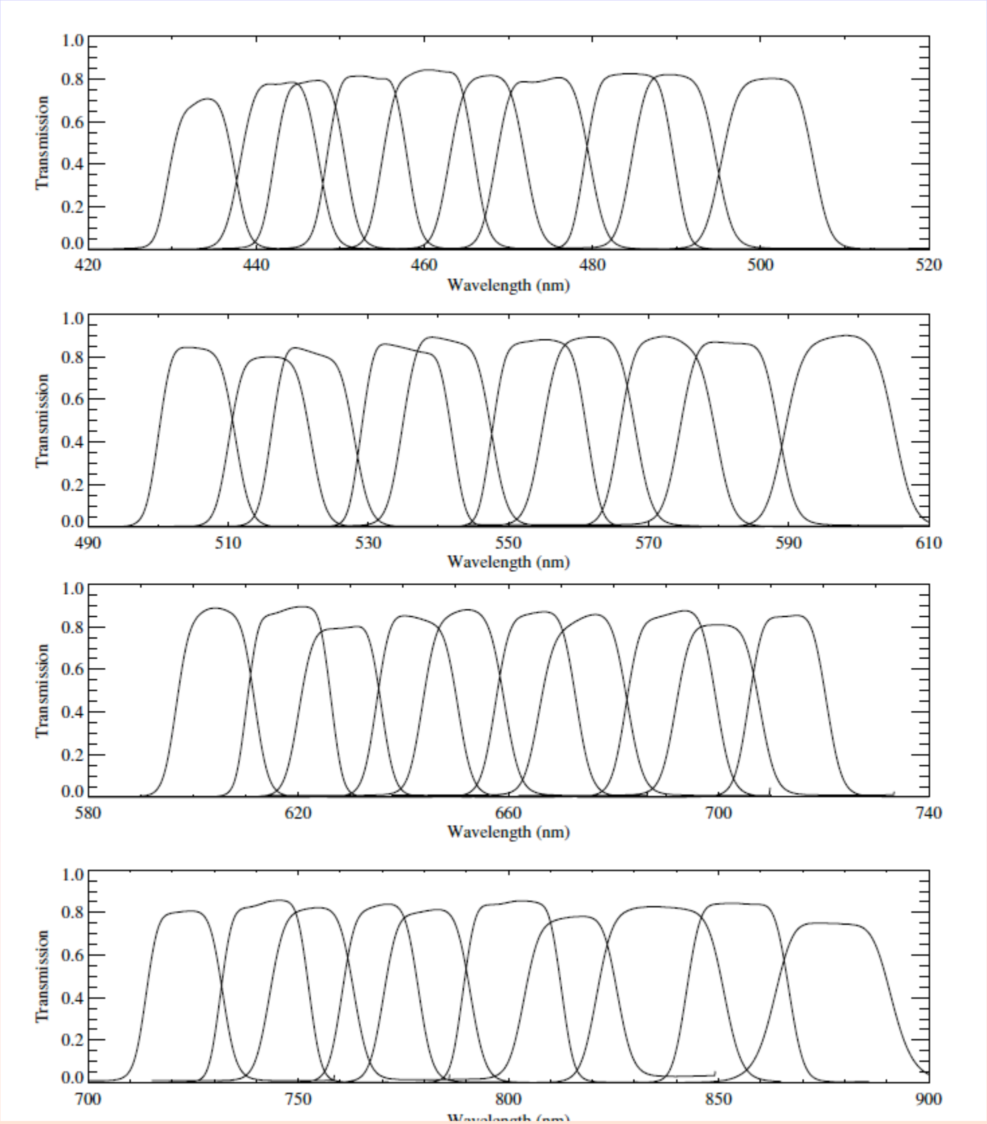
Interferometry-I: Fabry-Perot imaging
Ground-based instruments: RSS

Dual-etalon + filter order blocking scheme



Order selection with interference filter and dual etalons. Solid curve: SG etalon; dashed curve: filter; dotted curve: MG etalon.

Interferometry-I: Fabry-Perot imaging
Ground-based instruments: RSS

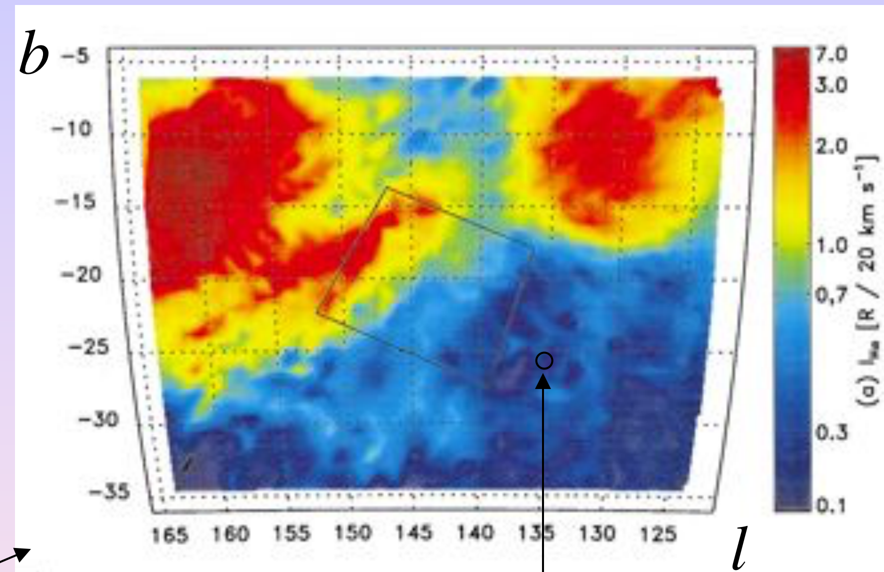


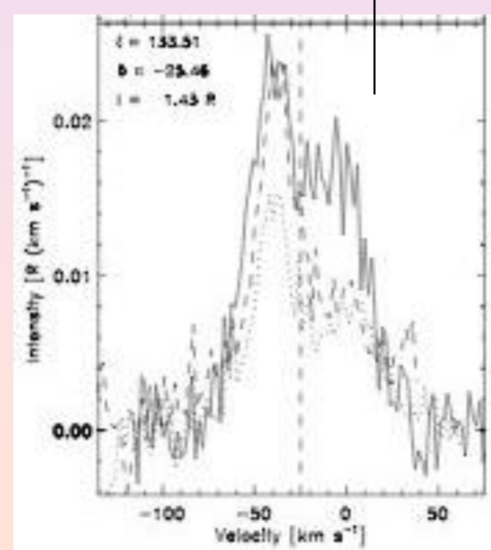
Suite of NB filters for FP …
…but remember you can use them for imaging or for filtered spectroscopy (MMS mode)

Interferometry-I: Fabry-Perot imaging
Ground-based instruments

- Two extremes:
- RSS, SALT 9.2m
  - **Imaging** FP
  - 150 mm etalons
  - 9200 mm telescope
  - 8 arcmin FoV, 0.2 arcsec sampling
  - R = 300-9000
- WHAM

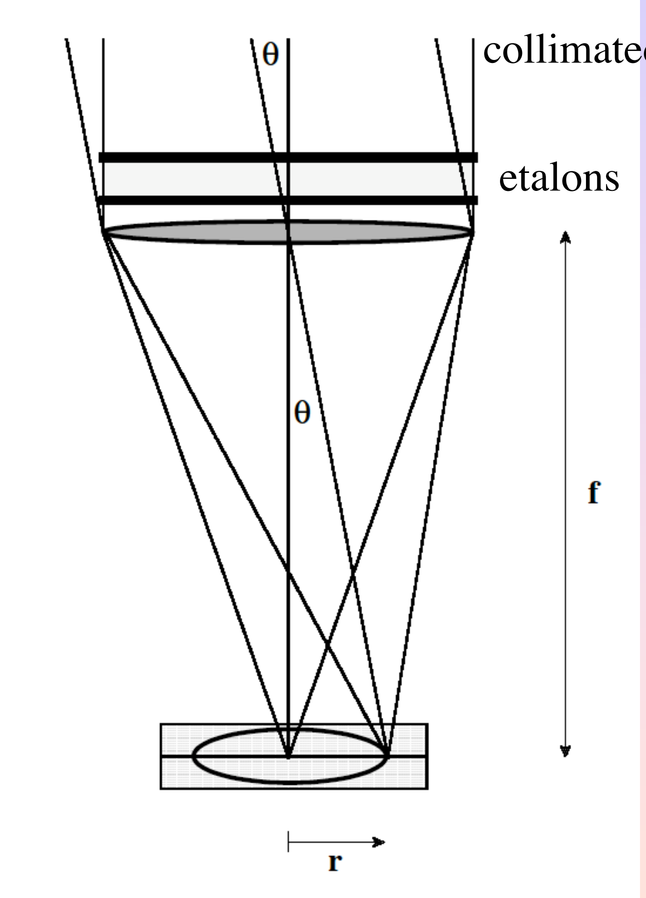
  Wisconsin Hα Mapper
  - **Non-imaging FP**
  - 150 mm etalons
  - 600 mm telescope
  - 1 deg FoV and sampling
  - R = 25000





Interferometry-I: Fabry-Perot imaging
Ground-based instruments: WHAM

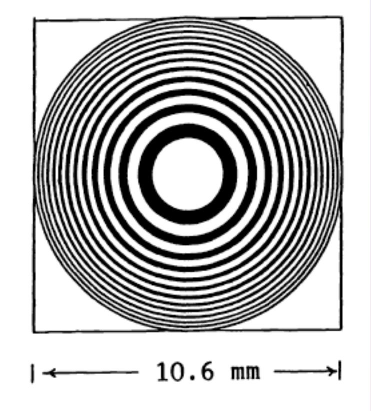
- An imaging FP



collimated light

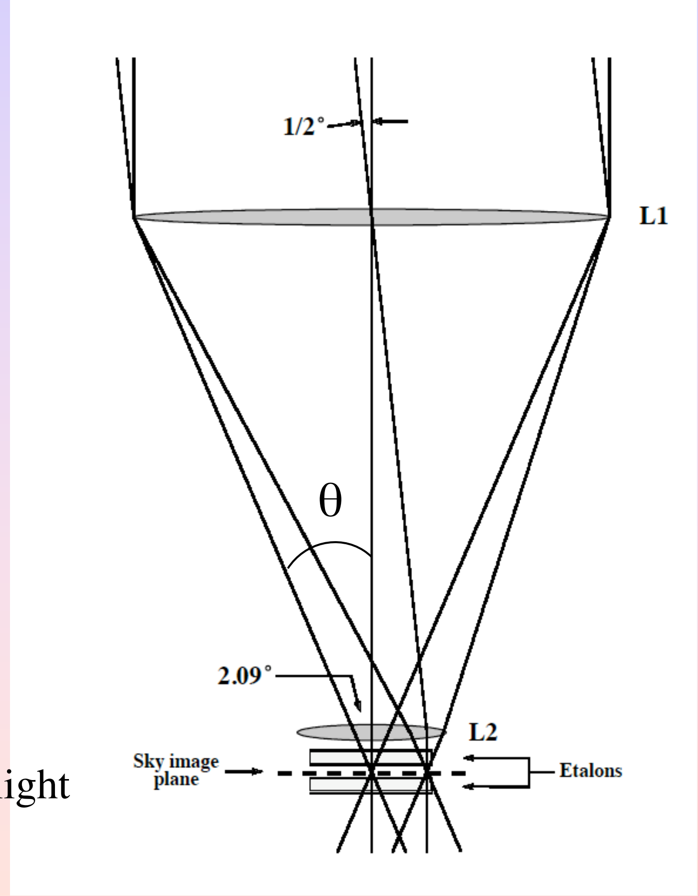
etalons

At the detector:



converging light

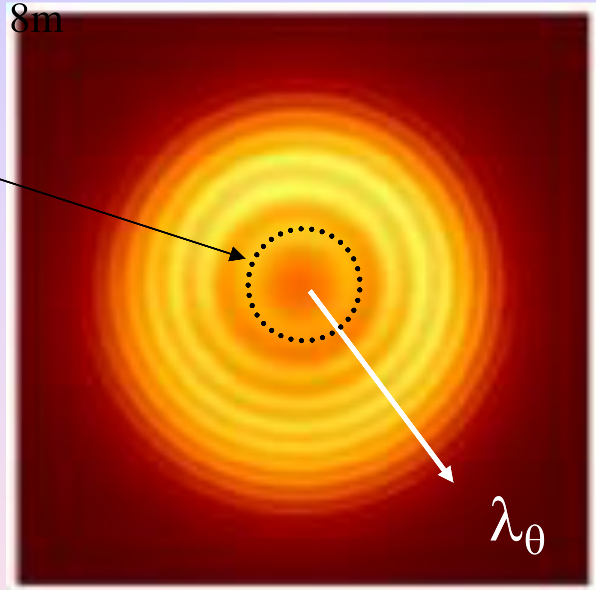
- A non-imaging FP



What determines the number of rings?

Interferometry-I: Fabry-Perot imaging
Bull's eye (Jaquinot spot) and rings - *revisitus*

Hartung et al.'04 NACO, VLT 8m



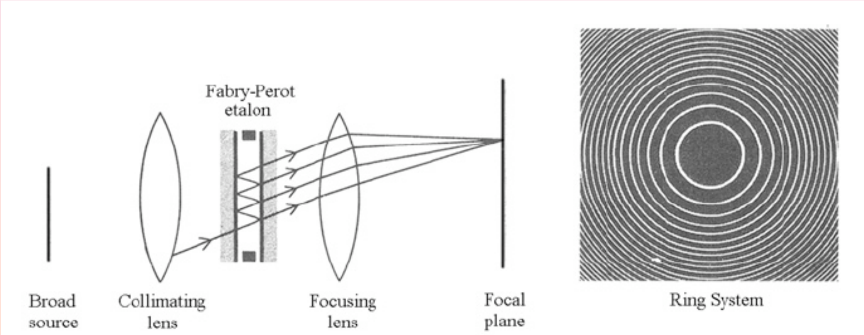
- **The bull's eye:**
  - What θ so that $\lambda_0/|\lambda_0-\lambda_\theta| < R$?
  - $\theta_{max} = (2/R)^{1/2}$
  - This quantity is *independent* of the telescope, and is a property of the etalon.

Where does this come from?

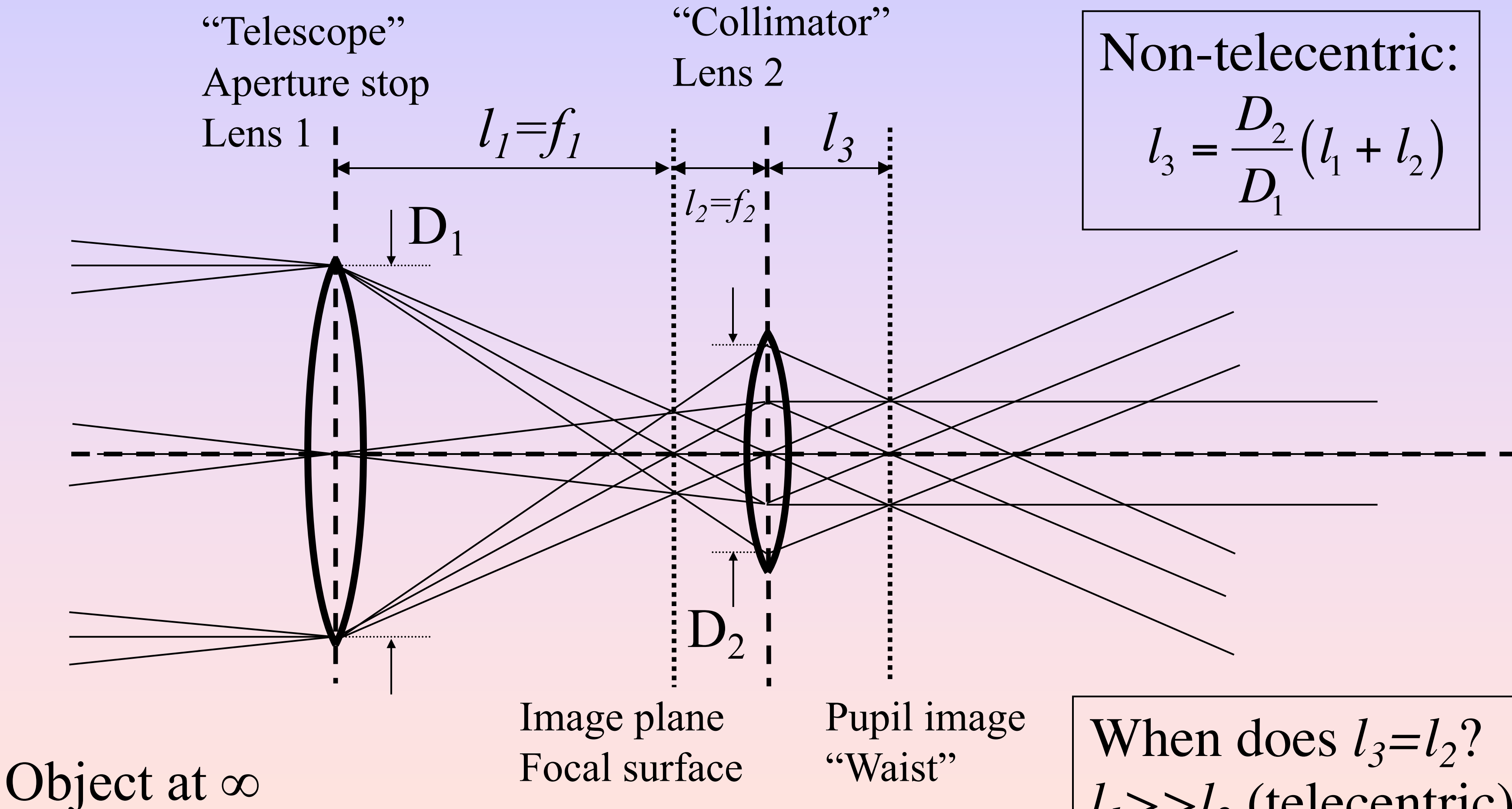
What's the angle of the nth ring?

How does the ring area (within the resolution element) change with n?

- Couple to a telescope to modify angular resolution:
  - $A\Omega$ is conserved
  - $\alpha = \theta\ D_e / D_T$
    - o α = angle on the sky
    - o θ = angle on the etalon
    - o D_e= etalon diameter
    - o D_T = telescope diameter



Objects, Images, Pupils

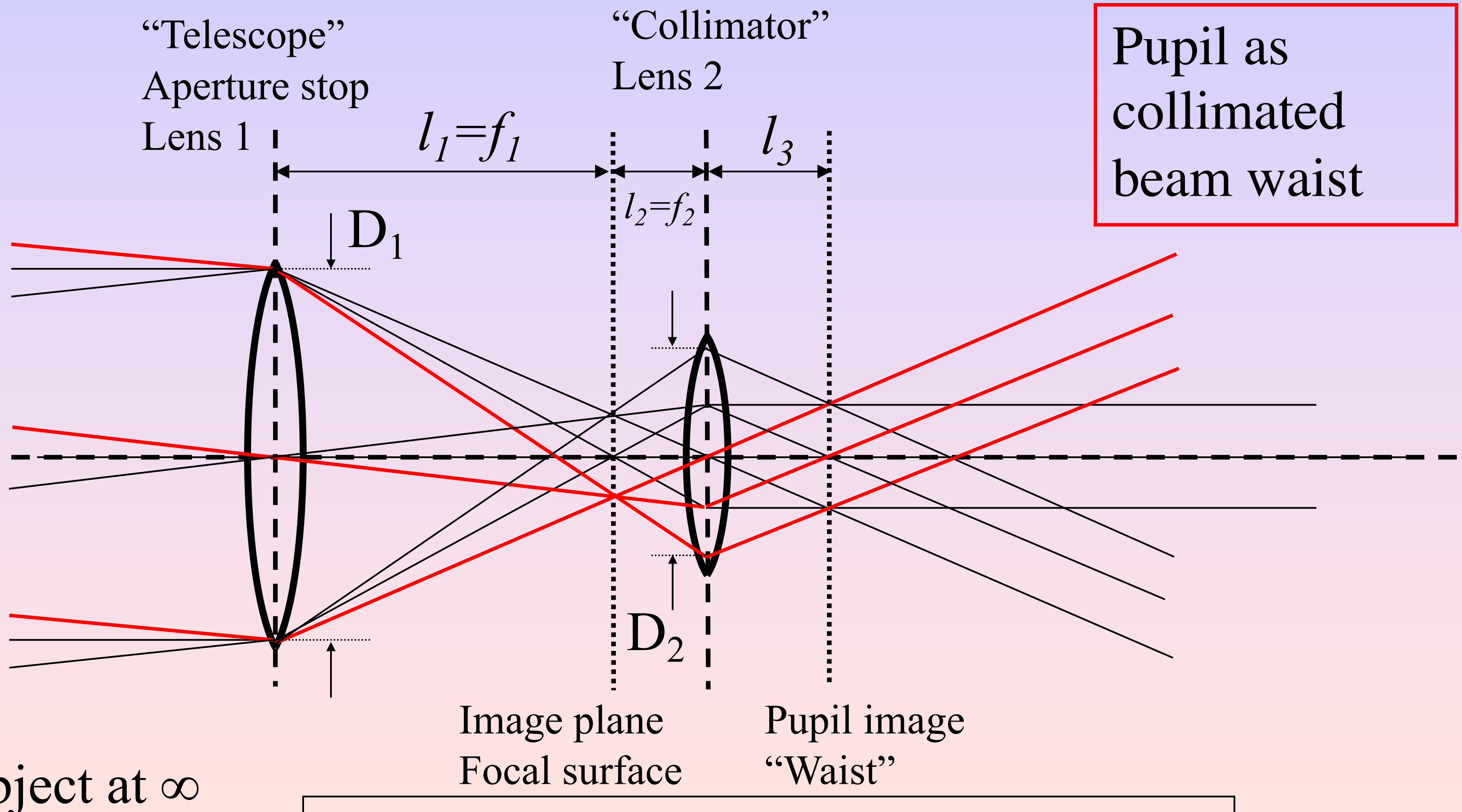


Non-telecentric:

$$l_3 = \frac{D_2}{D_1}(l_1 + l_2)$$

When does $l_3 = l_2$?
$l_1 >> l_2$ (telecentric)

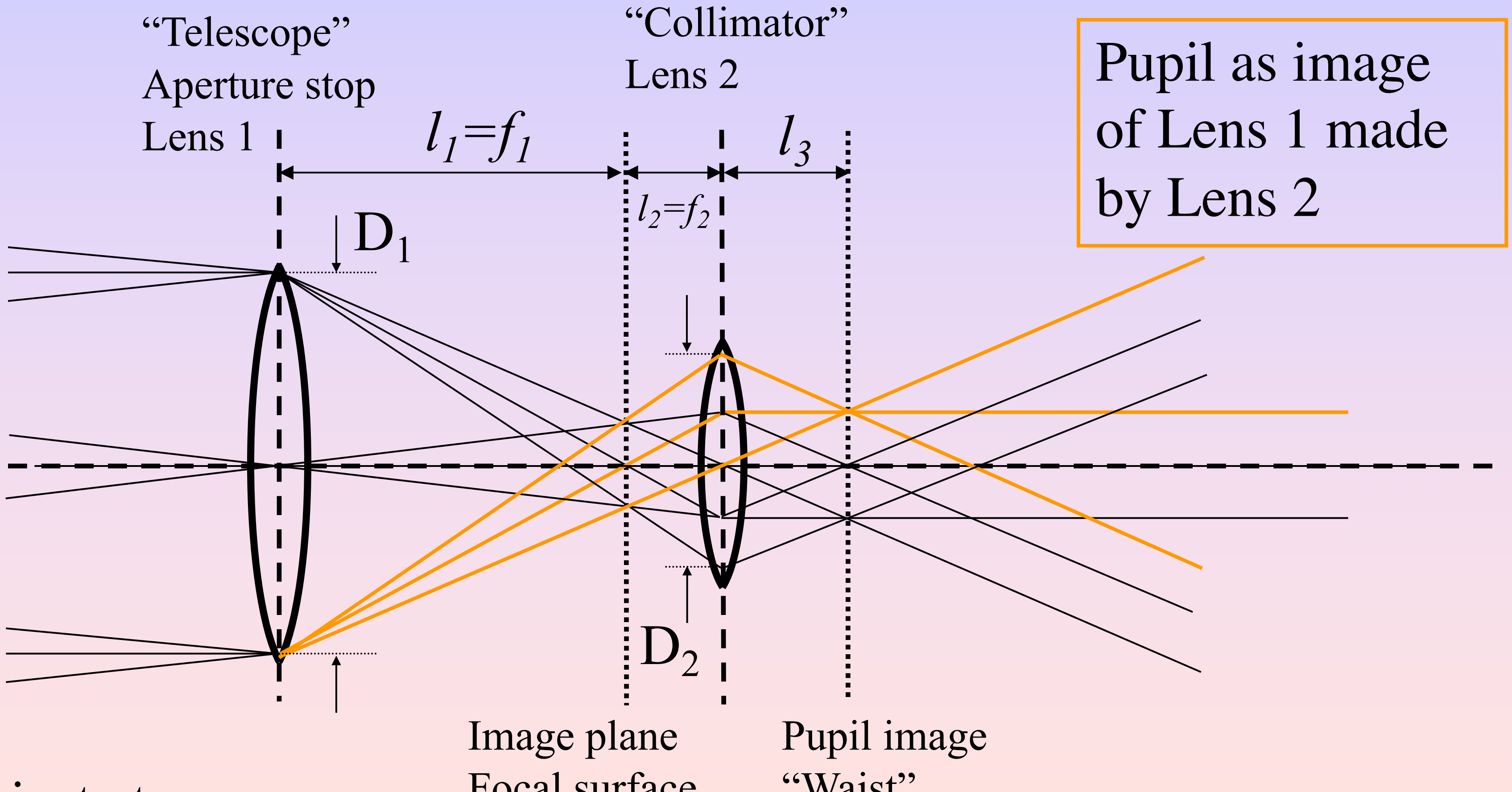
Objects, Images, Pupils



Pupil as collimated beam waist

Pupil: cross-section of light-bundle where light from all field angles in focal plane completely overlap. This is an image of the telescope primary and its associated stops.

Objects, Images, Pupils



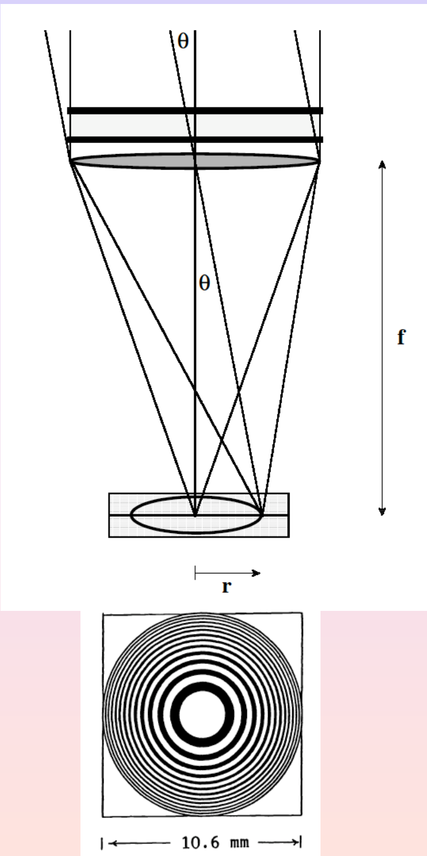
Pupil as image of Lens 1 made by Lens 2

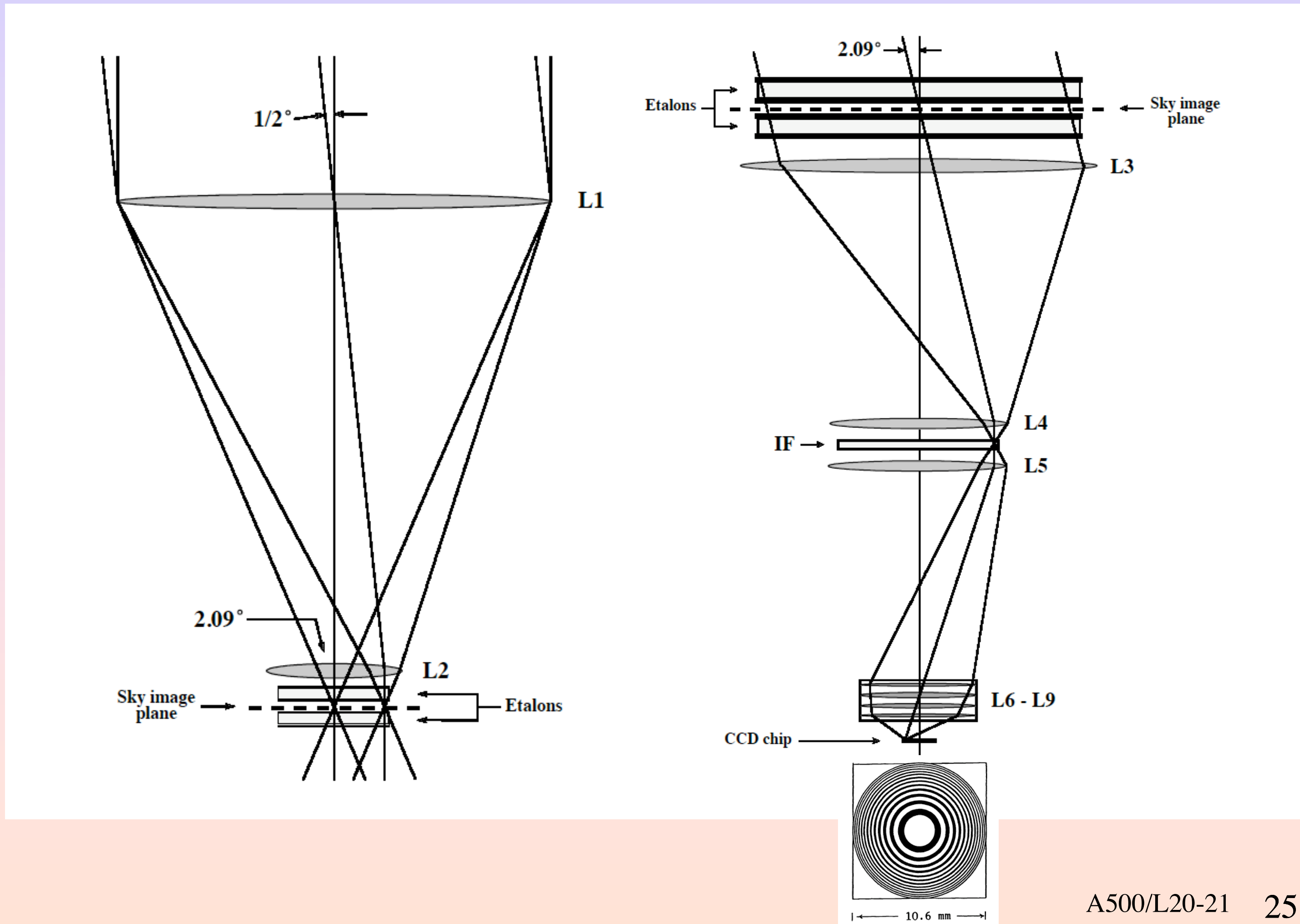
Object at ∞

Pupil: cross-section of light-bundle where light from all field angles in focal plane completely overlap. This is an image of the telescope primary and its associated stops.

Interferometry-I: Fabry-Perot imaging
Ground-based instruments: WHAM

- An imaging FP
- A non-imaging FP





Interferometry-I: Fabry-Perot imaging

Fabry-Perot instruments - summary list

- Existing optical instruments
  - GHASP, HPO 1.9m
  - RFPI, CTIO 4m
  - RSS, SALT 9.2m
- Future optical instruments
  - OSIRIS, GTC 10.4m
- Existing infrared instruments
  - NACO, VLT 8,
- Future NIR instruments
  - FGS-TF, JWST 6.5m ⇐ Never made it

This list is incomplete

Interferometry-II:
Spatial-heterodyne spectroscopy

- What is an SHS?
  - A Michelson interferometer with gratings replacing the mirrors
  - Principles of operation
  - Advantage over Michelson: no stepping required
  - Field widening-possible
  - Long-slit and lenslet feeds possible
  - Non-lossy geometries possible
  - Cross-dispersion possible (tilt one grating), but the same fundamental limits apply concerning 3D information formatted into a 2D detector!
- low-cost, diffraction-limited high-resolution capability
- multiplex disadvantage: implications for design and use

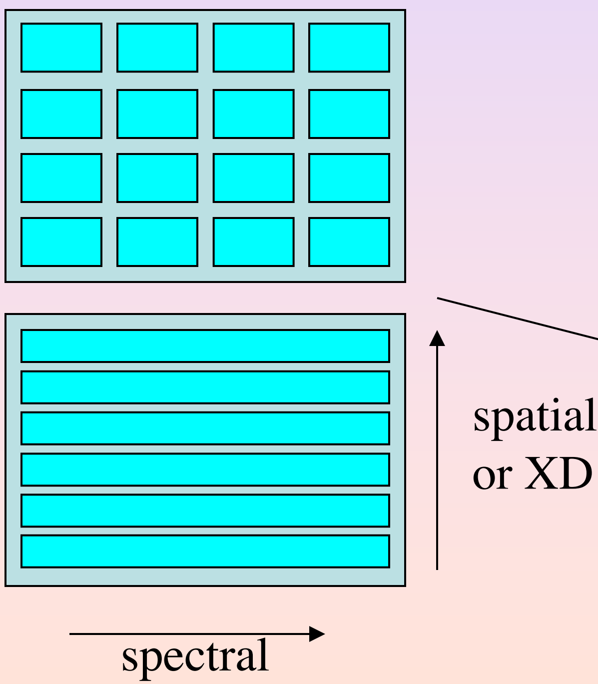
Interferometry-II:
Spatial-heterodyne spectroscopy

Instrument lay out

Pupil, slit or lenslet array can be placed here

lenslets

slit



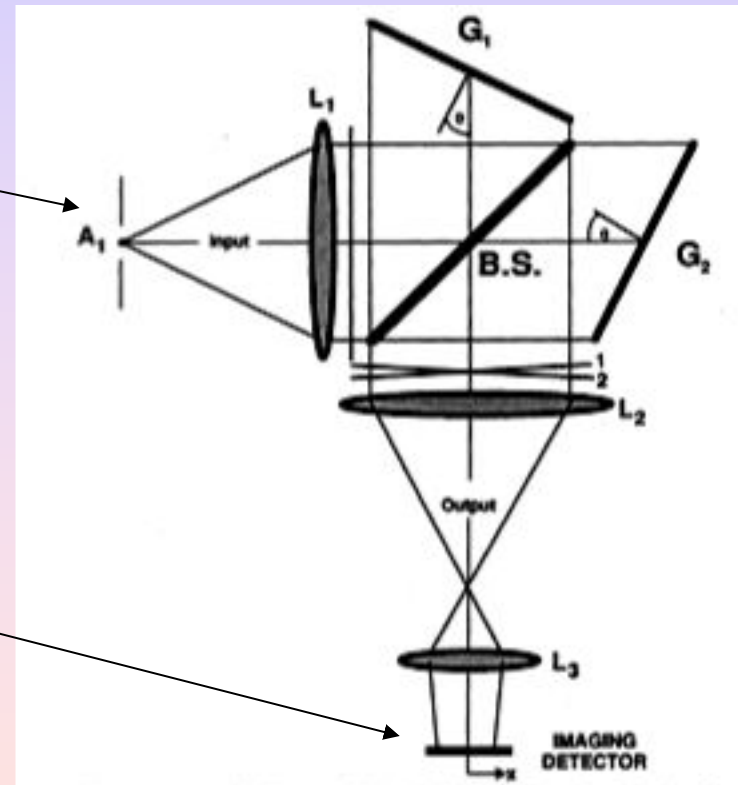
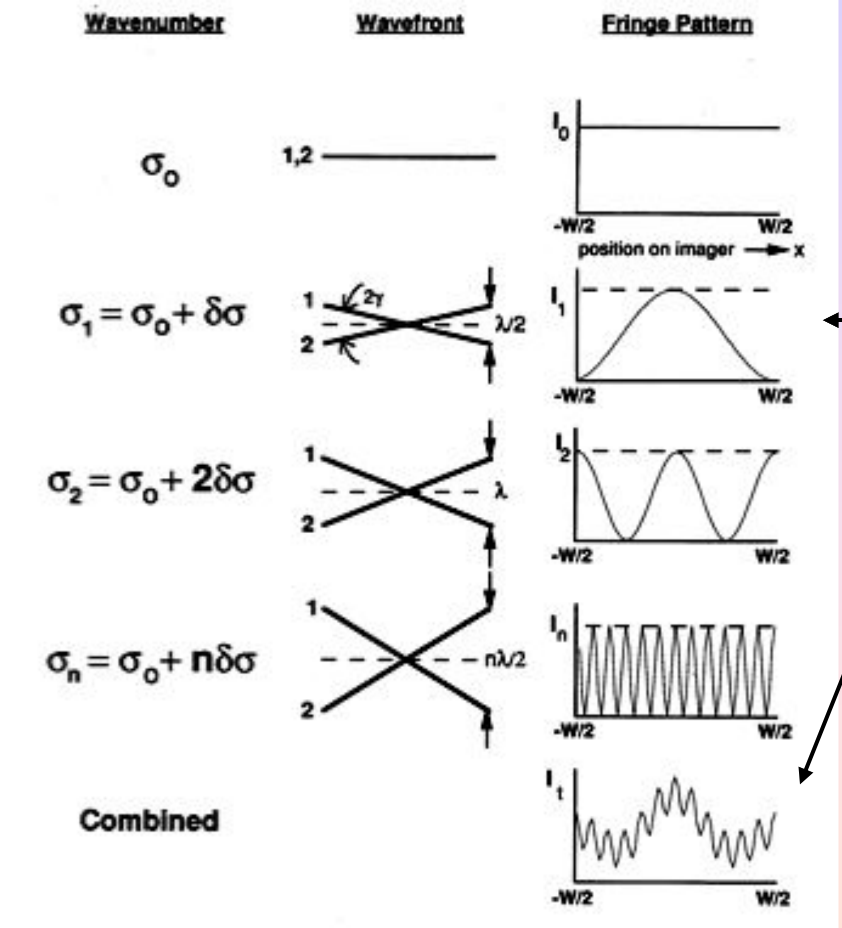


FIG. 1.—Schematic diagram of the basic SHS configuration. Wavelength-dependent Fizeau fringes which result from crossed wavefronts 1 and 2 at the exit of the interferometer are recorded along the x-direction by a position-sensitive detector. The Fourier transform of the fringe pattern recovers the spectrum.

Interferometry-II:
Spatial-heterodyne spectroscopy

Principles of operation

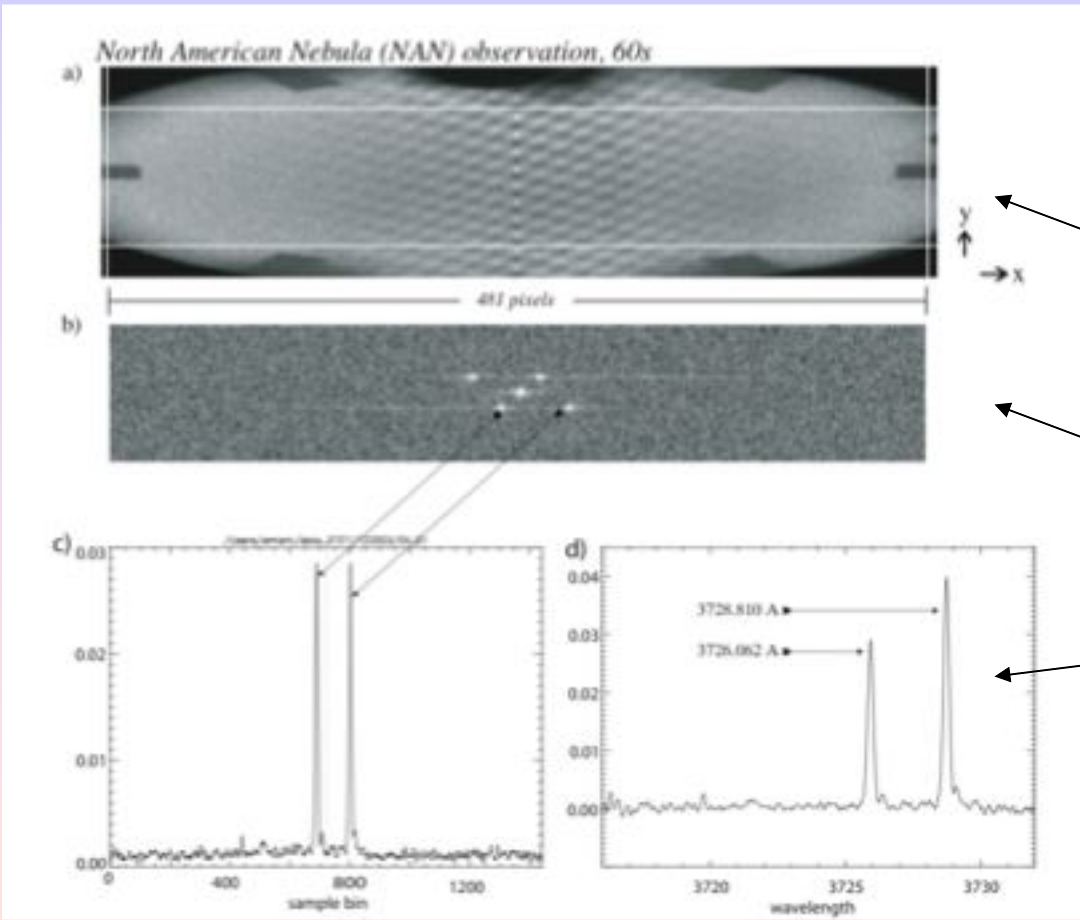


- Gratings diffract light at wavelength-dependent angles.
- Wavefronts produce interference patterns with frequencies set by wavelength.

- *Resolution* is set by the grating aperture diameter.
- *Bandwidth* is set by the length of the detector (how many frequencies can be sampled depends on the number of pixels)

The signal is heterodyned about the frequency of the central wavelength.

Interferometry-II:
Spatial-heterodyne spectroscopy



PBO SHS data

courtesy Harlander, Roesler, and Reynolds

OII interferogram

with cross-dispersion via grating tilt

FT power spectrum

Wavelength calibrated, filter-corrected [OII] spectrum

Resulting [OII] spectrum

Interferometry-II:
Spatial-heterodyne spectroscopy

Field-widened Michelson

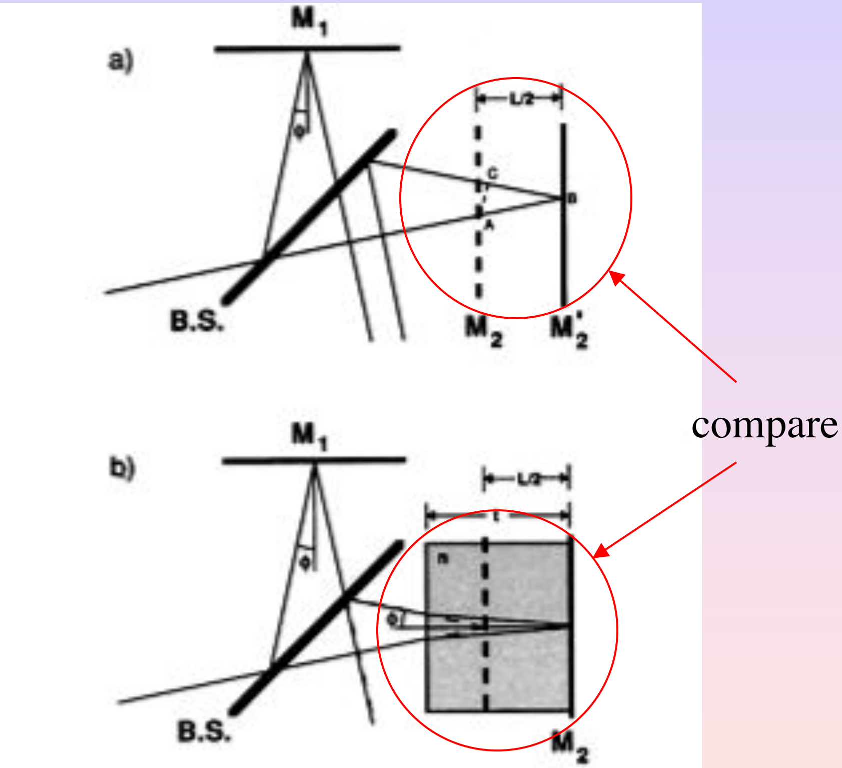


FIG. 3.—(a) Off-axis properties of a Michelson interferometer. When mirror at M_2 is moved to position M_2', the path difference in the system becomes a function of off-axis angle ϕ. If the path difference for axial rays is L, as shown in the figure, then the off-axis path difference, denoted in the figure by $\overline{AB} + \overline{BC}$, is $L \cos \phi$. (b) Field-widened Michelson interferometer. When a material with refractive index n and thickness t is placed in front of the displaced mirror M_2', the quadratic dependance on path difference with off-axis angle is eliminated. The thickness of the material is chosen so the geometric images of M_1 and M_2 appear coincident.

Field-widened SHS

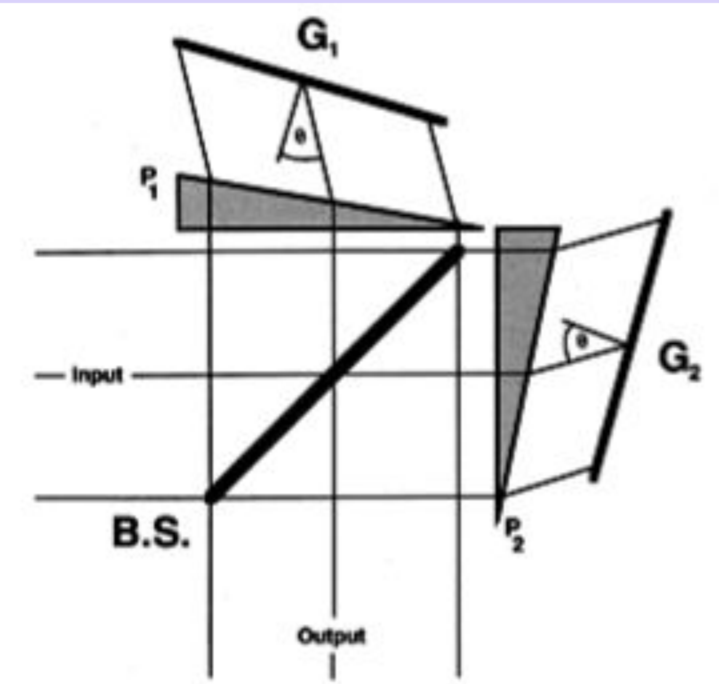
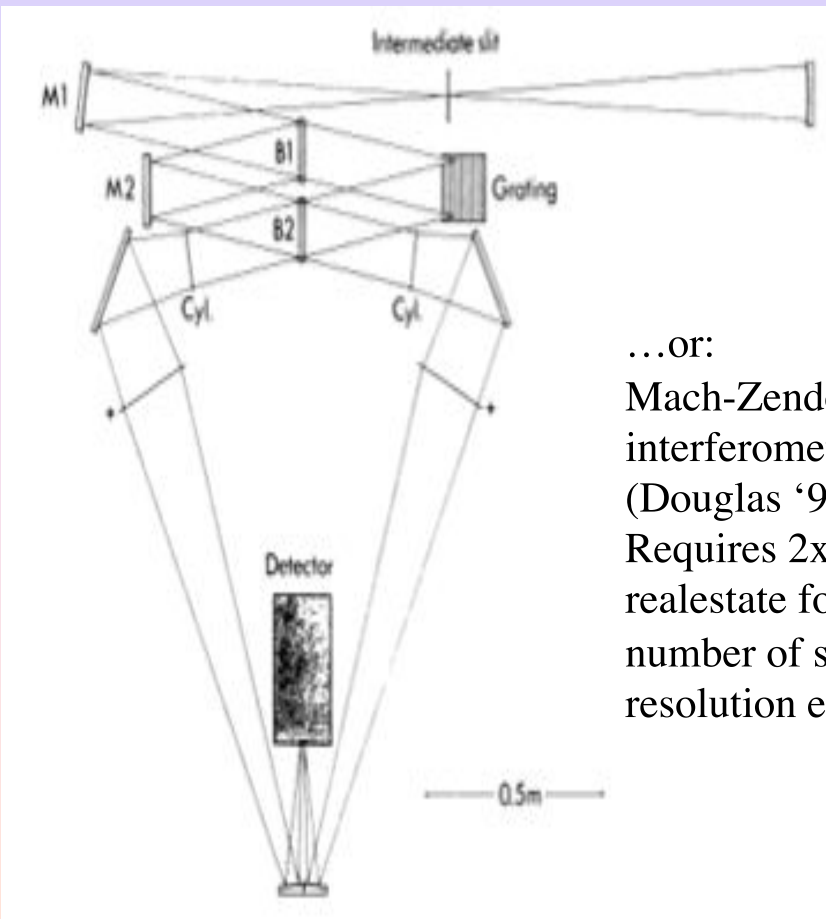


FIG. 4.—Field-widened SHS system. Prisms P_1 and P_2 are chosen so the diffraction gratings appear, from a geometrical optics point of view, coincident and perpendicular to the optical axis.

Prisms give gratings geometric appearance of being perpendicular to the optical axis.

Interferometry-II:
Spatial-heterodyne spectroscopy

Standard Michelson and SHS lose half the light right from the start:



…or:
Mach-Zender style interferometer (Douglas '90).
Requires 2x detector realestate for same number of spectral resolution elements.

But efficient configurations do exist:

Add prisms for field-widening
Or gratings for increased R

Perfect application for holographic grating

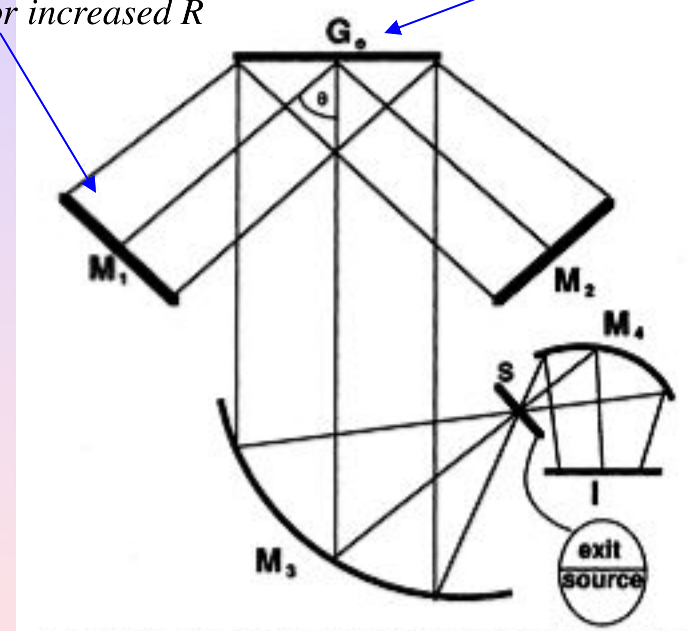


FIG. 5.—Schematic diagram of the all-reflection SHS configuration. Light enters the system through the lower half of split aperture S and exits through the upper half, after which it is imaged by M_4 onto an imaging detector I. The diffraction grating acts as both the beam splitter and dispersive element in the system.

Harlander et al. '92

Interferometry-II:
Spatial-heterodyne spectroscopy

- Low-cost, diffraction-limited high-resolution capability
  but . . .

- Multiplex disadvantage:
  - $S/N_{SHS} = S/N_{GS} * (f/2)^{1/2} (S_{SHS}/S_{GS})^{1/2}$
    - S/N_{SHS}, S/N_{GS} = signal to noise in SHS and grating spectrometer
    - S_{SHS}, S_{GS} = total photon signal "
    - f = fraction of total signal in a given spectral channel
      - f < 1, and decreases with bandwidth
  - filter out OH lines (make f as large as possible)
  - choose small band-width

- Implications for design and use:
  - Make f as large as possible
    - filter out OH lines (make f as large as possible)
    - choose small band-width -- but more than Fabry-Perot!

The detector limit-I:
Three into two dimensions revisited

Sampling the data cube: volumes sampled by equal detector elements