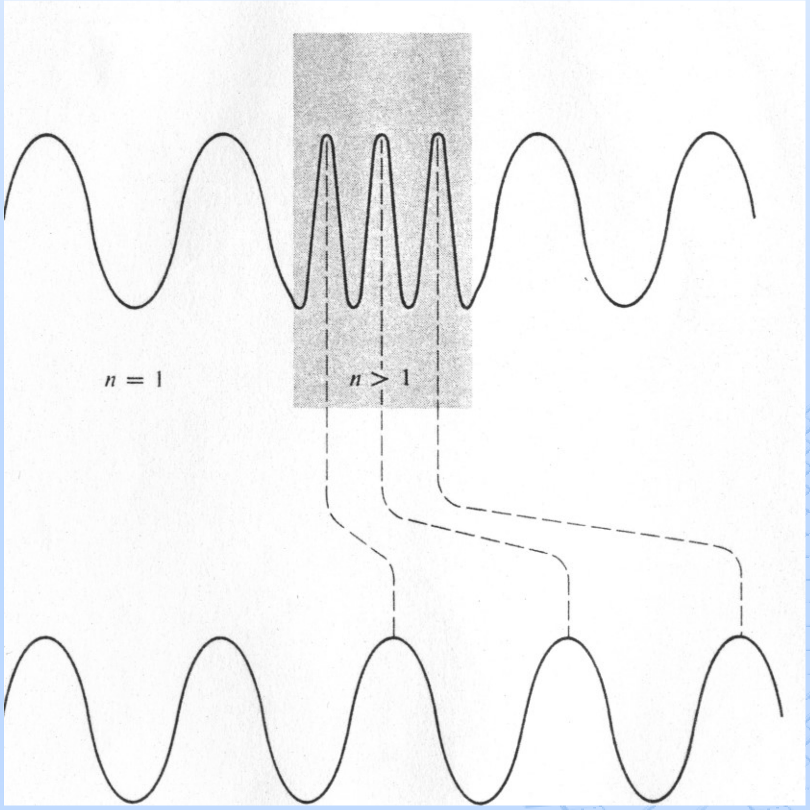
OPTICS Concepts related to Astronomy

A. Gilliotte – Optics / Seon 2020

Basic Optics - 1

- Propagation speed is uniform and constant within the vacuum → ~ 299792 km/s
- Speed decreases when crossing a different medium



→ define the medium index or **index of refraction: n**

n = light speed in vacuum / light speed in medium

Speed/medium dependence

→ Refraction (Lens application)

Wavelength/medium dependent

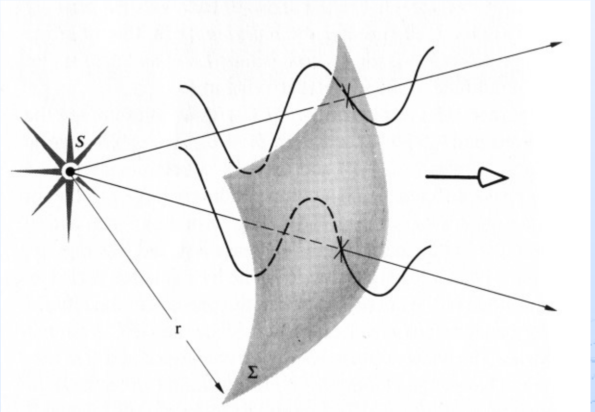
→ Chromatism (2nd effect !!)

Basic Optics - 2

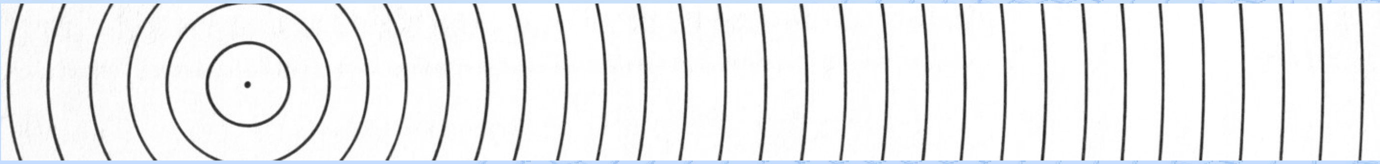
The Ray and the Wavefront:

<u>Very important concept</u>

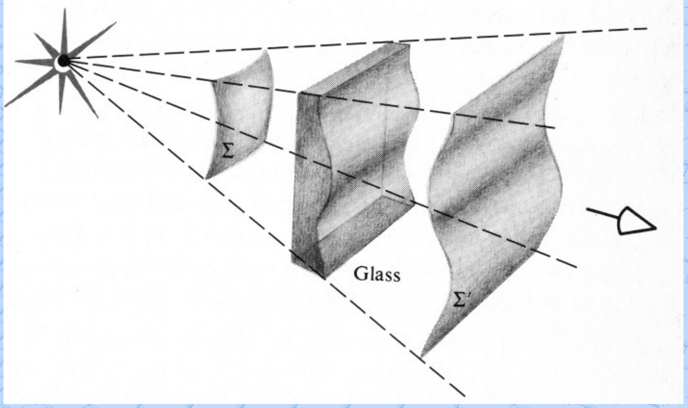
used in several optics topics.



Plane Wav.



Wavefront Propagation



Geom.Optics - 1

Unfortunately the wavefront issued from the object will be limited by the optical system (size, shape, ...) inducing the permanent effect known as **diffraction**.

The attainable perfection of an optical system will always be limited by diffraction effects

Geom.Optics - 5

What about **Field of view** ?, system **Efficiency** ?.

Unfortunately an optical system cannot be 100% efficient and allowing a full solid angle field coverage...

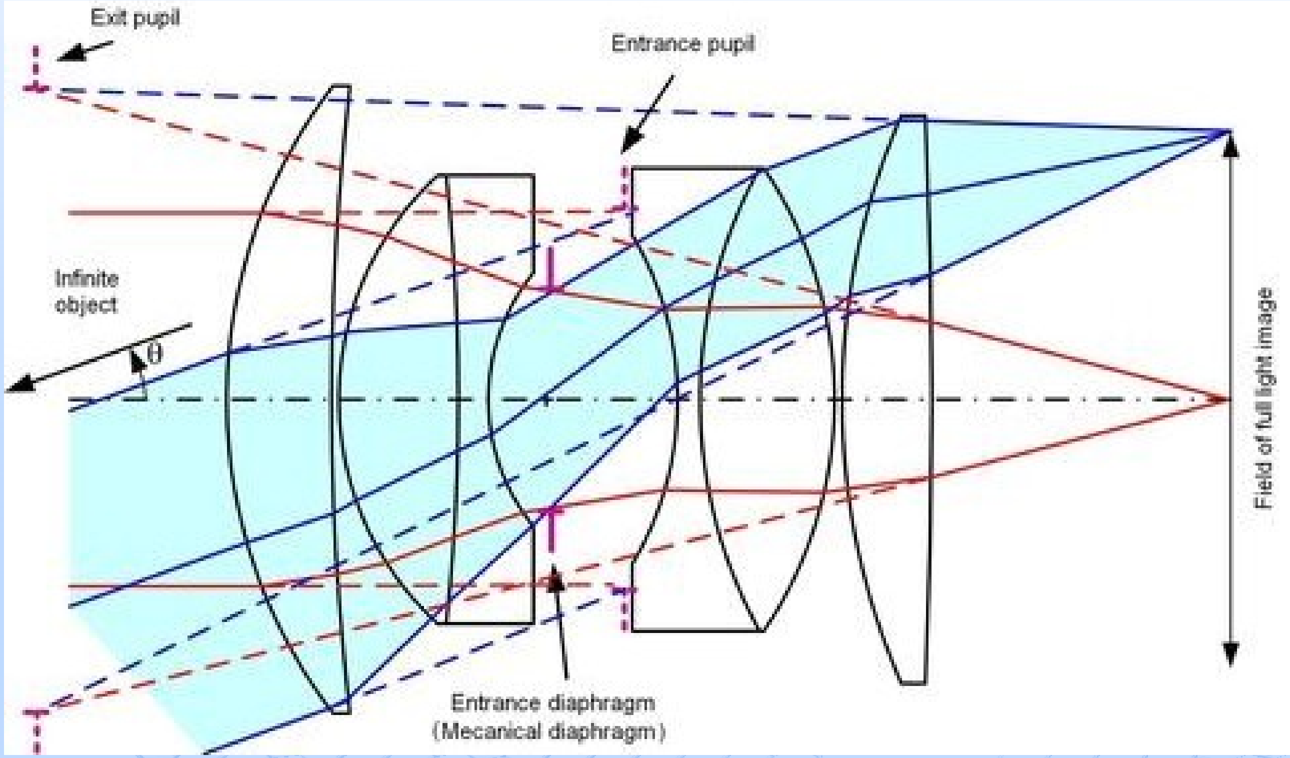
The optical surface or element size which determines the amount of light reaching the image is called : Aperture Stop

- Images of this stop along the system spaces are called: Pupils
  - On the object space → Entrance Pupil
  - On the image space → Exit Pupil

One single lens can be called by the "three" terms

Geom.Optics - 6

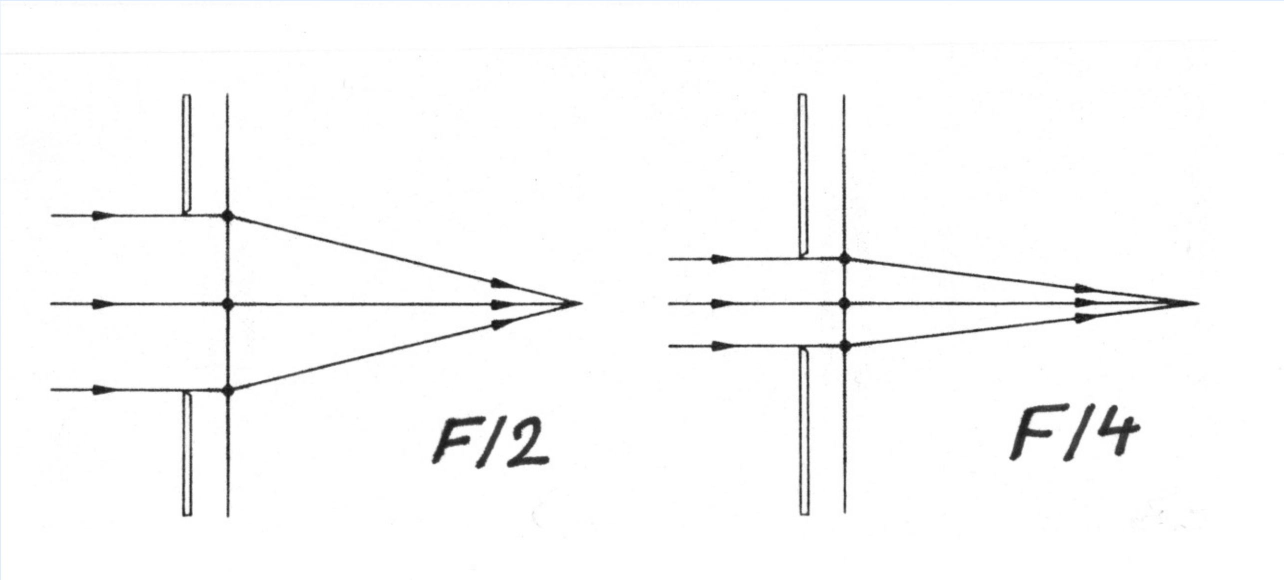
Example with more lenses



Related effect → Vignetting

Geom.Optics - 7

Another important parameter → **F/Number**



F/# = F / D

(F: focal, D: aperture diameter)

Geom.Optics - 8

Optics cannot delivers perfectly stigmatic images…

And the departure from ideal conditions is called : **Aberrations**

mainly classified in two groups depending or not of the wavelength

- Directly related to the refraction law reality (w/o approximation)

  [Snell : $n_i \sin i = n_t \sin t$ & $i = r$]

  i Incidence - t Transmitted - r Reflected

- Chromatics additional effect on refraction

Geom.Optics - 9

- **First order aberration** :
  - wavefront tilt (~ $\sigma\ \rho$)
  - defocus (~ ρ^2)

Field : σ

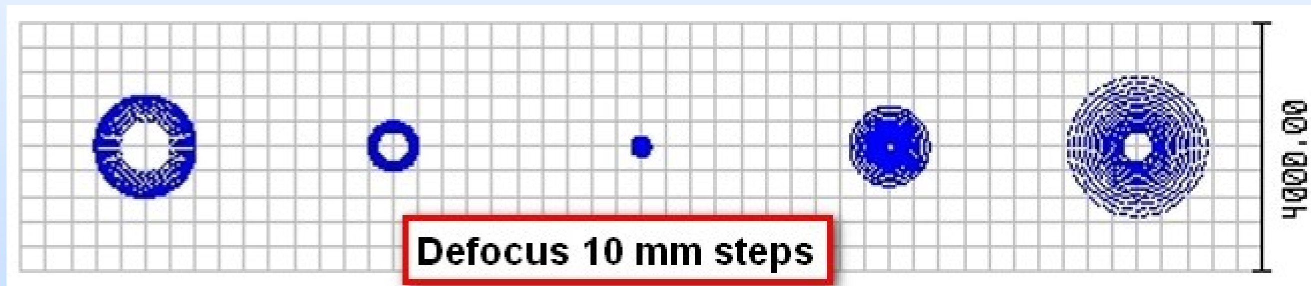
Apert : ρ

- **Third order aberrations** :
  - **SA** - Spherical aberration (~ ρ^4) → σ independent !
  - Field curvature (~ $\rho^2\sigma^2$)
  - **Coma** (~ $\sigma\ \rho^3$) → linearly σ dependent !
  - Distorsion (~ $\sigma^3\ \rho$) → cube σ^3 dependent !
  - **Astigmatism** (~ $\sigma^2\ \rho^2$) → square σ^2 dependent !

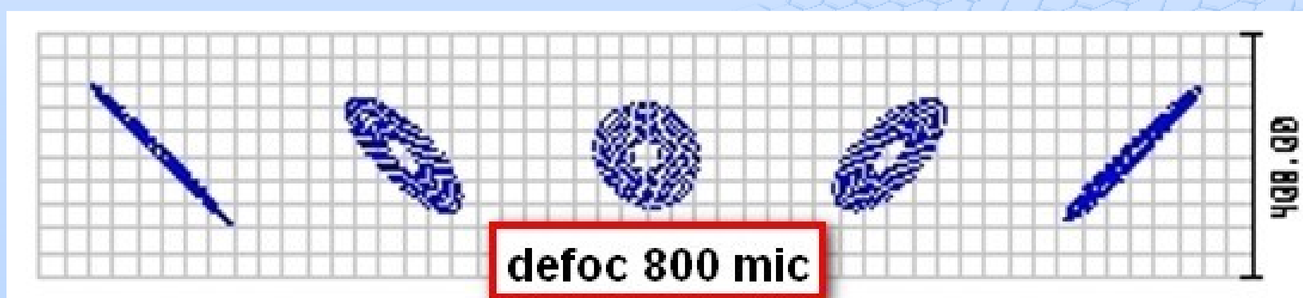
Geom.Optics - 10

Aberrations on Telescope optic beam !

SA effect



Astigmatism

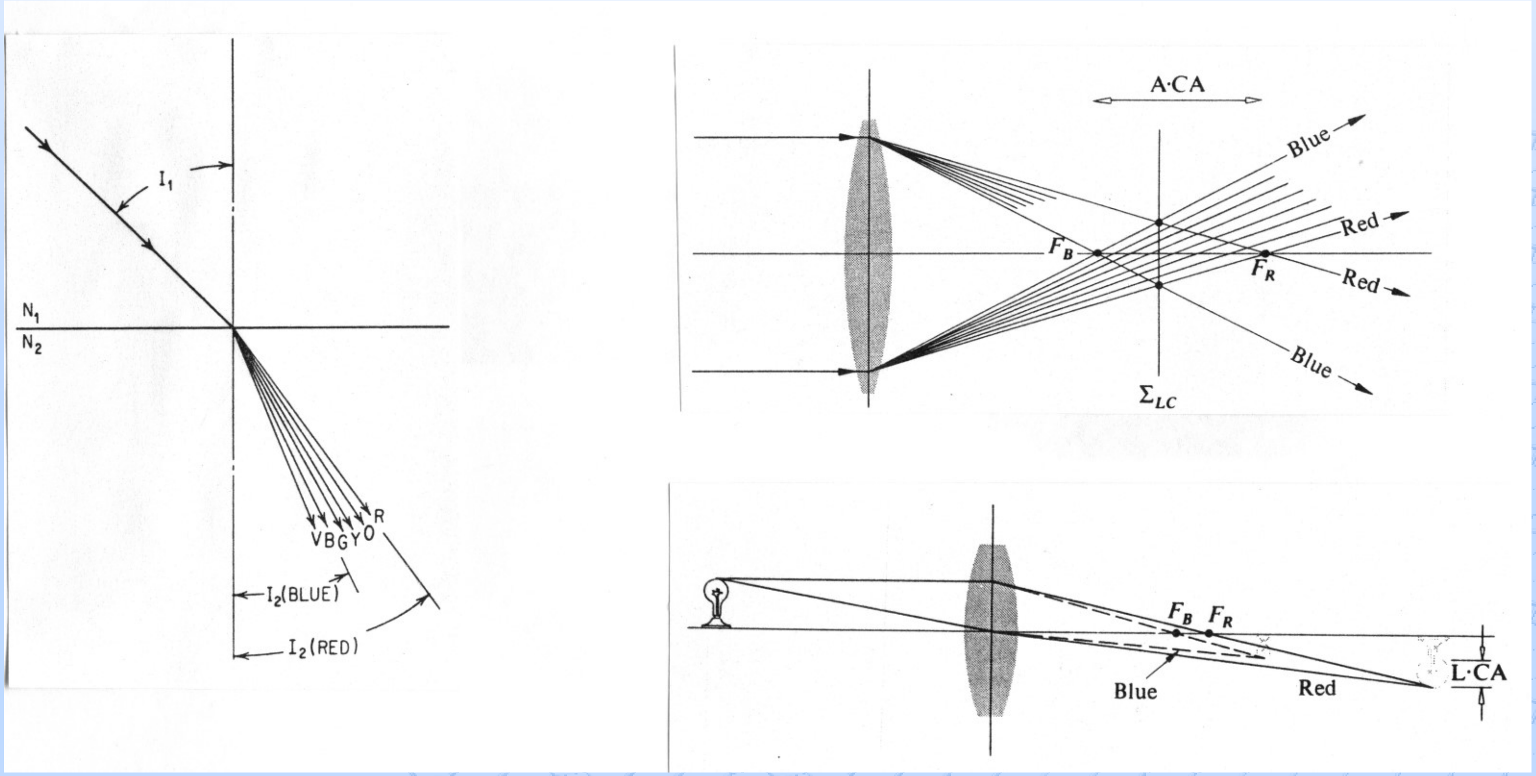


Coma

Geom.Optics - 11

- **The chromatic aberration**:

  Refraction dependent on wavelength.



Axial and lateral chromatism effects

Optics Physic. - 1

- Interaction of different waves in various planes of vibration:
  - Polarization: Plane of vibration effects
  - Interference: Interferential Filters, Fabry-Perot, …
- Interaction of optical elements “size” on wave propagation:
  - Diffraction : Physical limits of perfect optics
- Wave interaction with the medium related to Astronomy:
  - Coherence
  - Turbulence: Thermal contribution
  - Adaptive optics: a way to minimize this interaction

Optics Physic. - 2

Polarization:

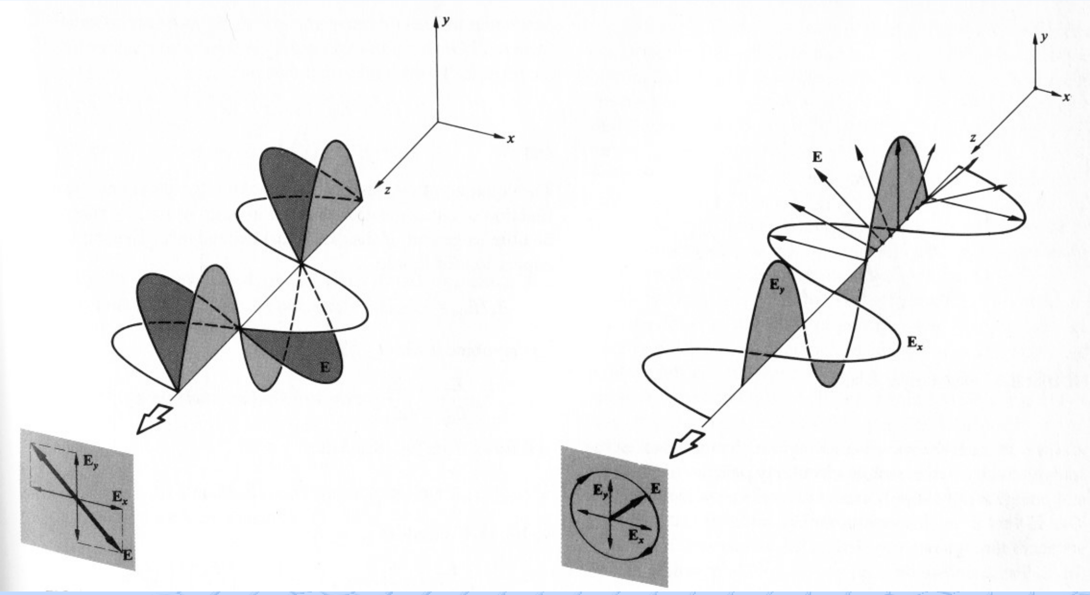
Linear / Circular

Polarizers:

Dichroism, Reflection,

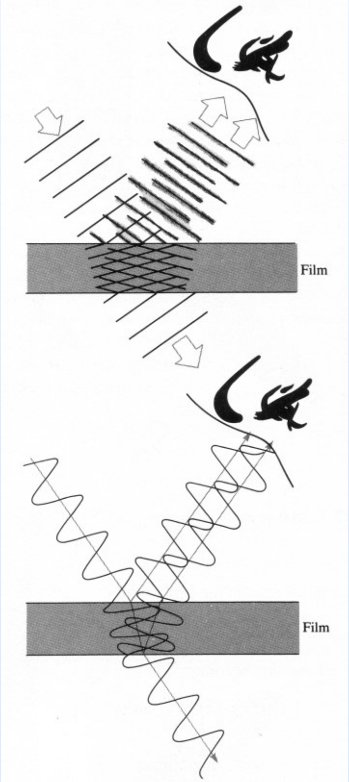
Bi-refringence, Scatter

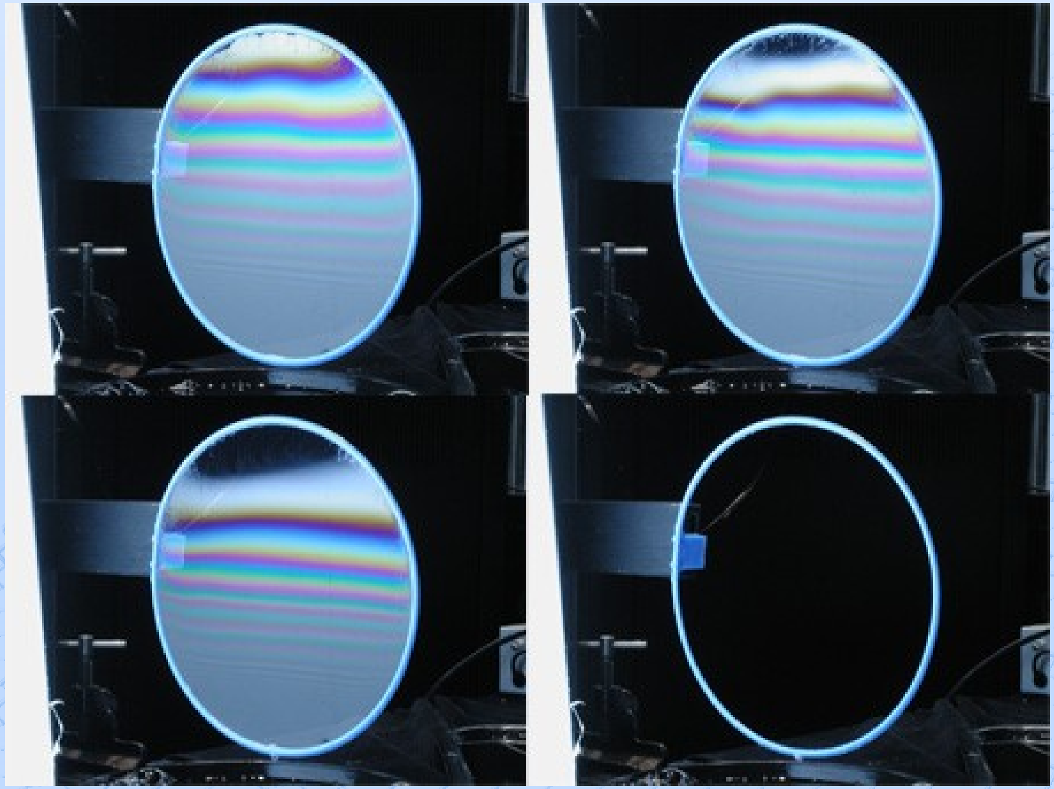
Wollaston prism, Retarders



Optics Physic. - 3

Interferences:





Optics Physic. - 4

<u>Interferences/Diffraction</u>:

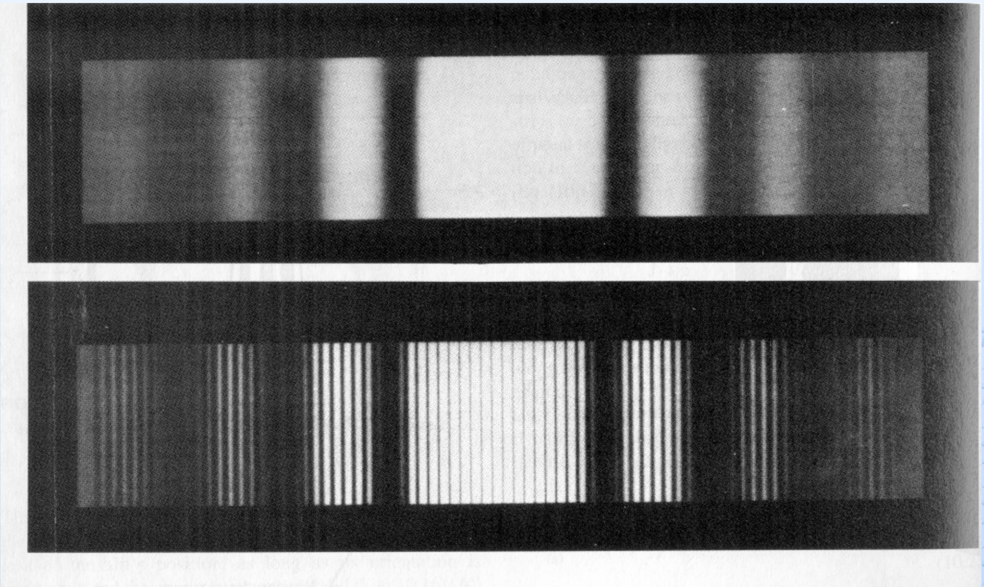
Single slit: minima at m λ / b

b slit width → Diffraction

Double slit: minimas at m λ / a

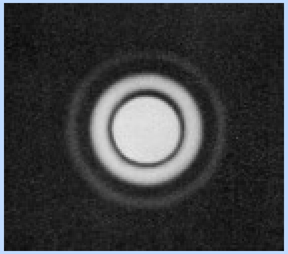
& at m λ / b, a slit separation

→ Interferences



➢ <u>Circular aperture effect:</u> **<u>The Airy disk</u>**

The first dark ring radius is r = 1.22 f λ / d (d diameter of Aperture Stop)



→ Two telescopes of 4 and 8m will resolve an angle separation of 3.1 10^{-2} and 1.6 10^{-2} arcsec

Optics Physic. - 5

Diffraction/Interference/Coherenc example.

Double circular aperture pattern

a- He-Ne laser

b- a) 0.5mm glass on one hole.

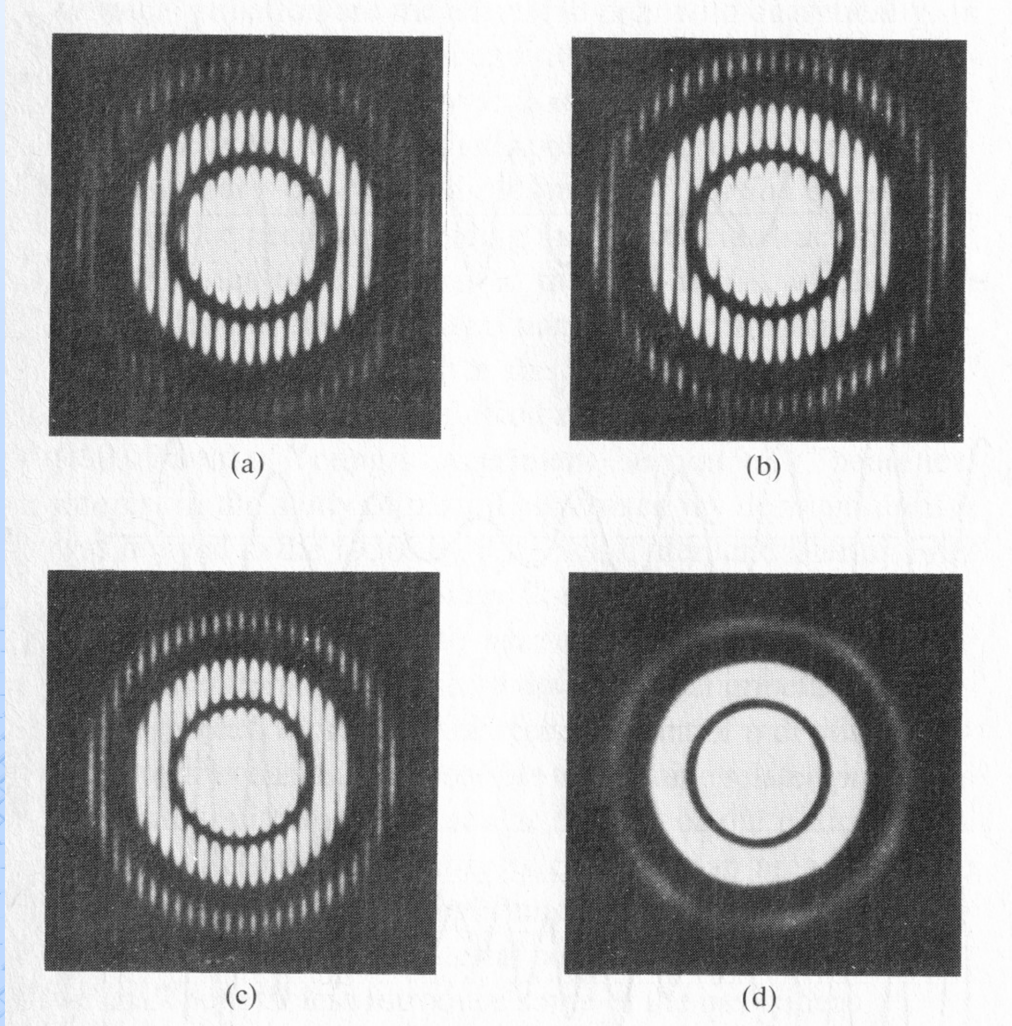
Despite the glass thickness the pattern remains → coherence

c- Hg lamp no glass plate

d- c) with glass plate

Pattern disappeared !

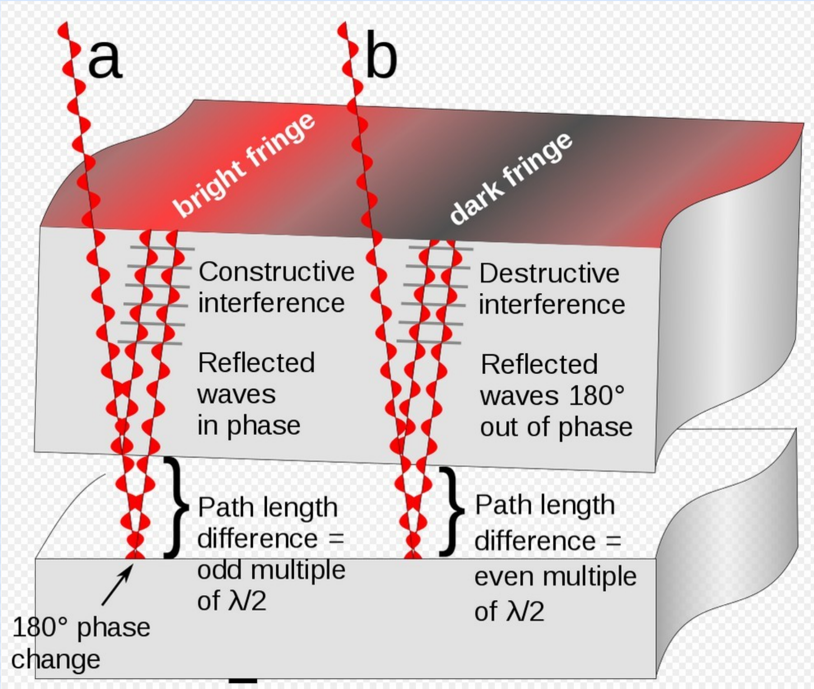
→ No more coherence



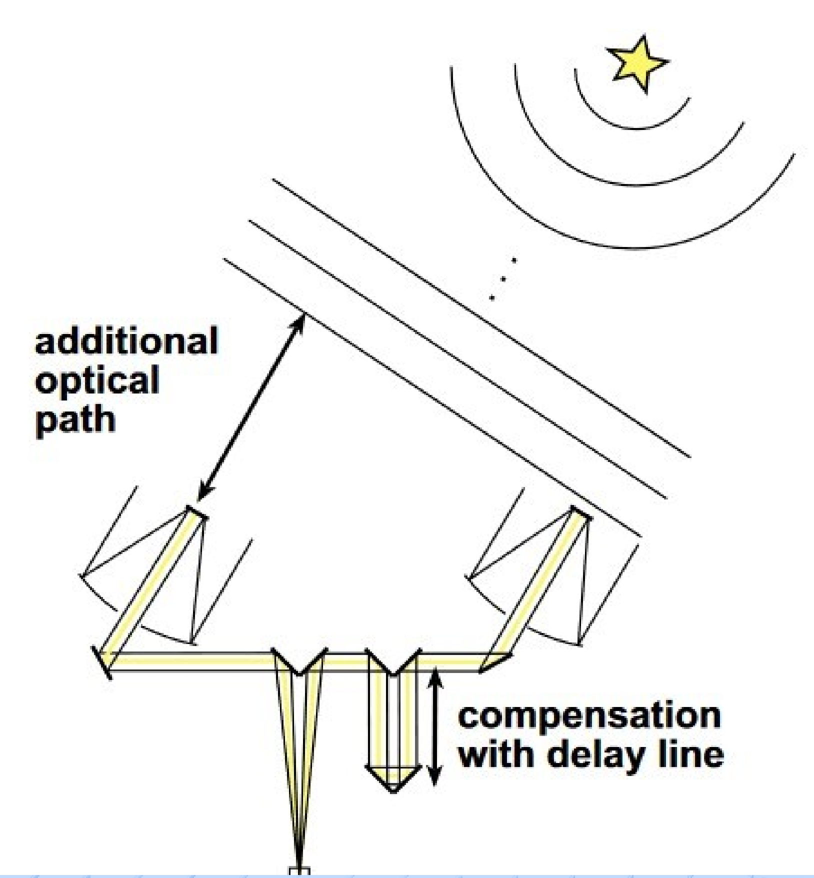
Optics Physic. - 6

Optical Path Difference: OPD.

Interference on air wedge



VLT interference



Turbulence - 1

Turbulence related to Astronomy

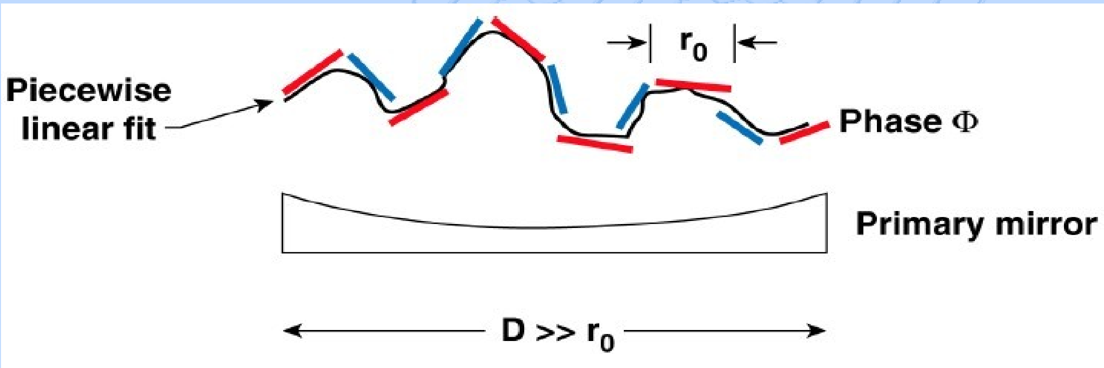
Atmosphere is a moving medium of turbulent air with effect on n index

Perfect plane wavefronts are distorted into a bumpy corrugated surface varying with time when crossing the atmosphere.

A few parameters represent this perturbation:

→ **r_0 or Fried parameter**: length scale on which the effect is significant.

For an optics $D < r_0$ the airy disk ϕ related to D. For an optics $D > r_0$ the airy disk ϕ related to r_0. $r_0 \sim \lambda^{6/5}$ and $r_0 \sim (\cos Z)^{3/5}$; Z being the zenith distance



Turbulence - 2

if r_0 ~ 25 cm at 500nm then 148 cm at 2.2µm and 910cm at 10µm

An r_0 of 25cm ~ to 0.4 arcsec seeing at 500nm

A so called "speckle" effect will be created, the pattern envelope is related to λ/r_0. For D >> r_0 the number of speckles increase. The pattern change depending on how fast the corrugated wavefront change.

→ **Seeing** : angular expression of r_0. $\omega_{min} \sim \lambda^{-1/5}(\cos Z)^{-3/5}$

→ **T_0** is the time scale on which the change of the turbulence effect is significant ~ order of 3 to 30 ms - $T_0 \sim r_0 / v$ (v medium speed)

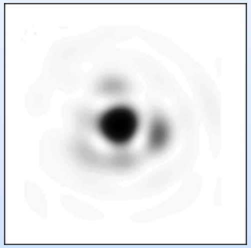
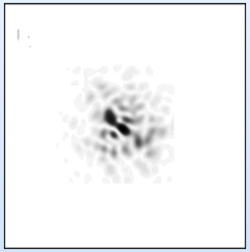
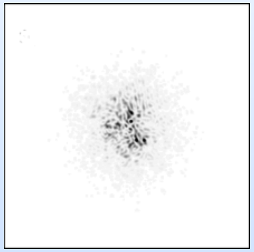
The shorter it is, faster should be the corrective actions

→ The outer scale **L_0** . (cut-off of turbulence spectrum at low frequencies), star FWHM for long exp. is not ω (under or over estimation !)

→ The Isoplanetic Angle **Θ** : Field angle with acceptable ~ r_0

Turbulence - 3

Very short exposures

D/r_0 ratio = 2  ratio = 7  ratio = 20 

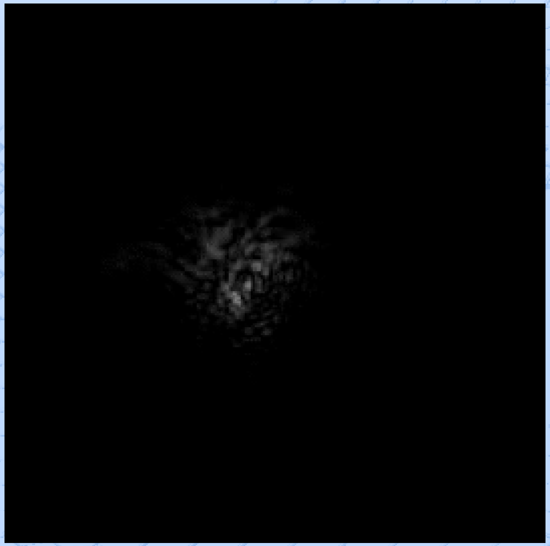
<u>With longer exposures the 3 images will be equivalent to the ω disk</u>

Very short exposures

slow motion (1/40 of normal)

Ratio D/r_0 ~ 10

Bad seeing



Turbulence - 4

<u>Additional turbulence local effects to the telescope</u>:

- Ground layer → thermal effect within few 10 m above the telescope
  - ➢ require optics not on the ground level but higher !
    (Dome C telescope above ground in Antartica)
- Local thermal effects :
  - Environmental effects (thermal effect within the dome)
    - ➢ Local turbulence control (wind effect)
    - ➢ Avoid any thermal sources, day cooling
    - ➢ ventilation
  - Optical element Temperature difference with the medium
    - ➢ Cooling
    - ➢ Ventilation on M1 (forced or induced)

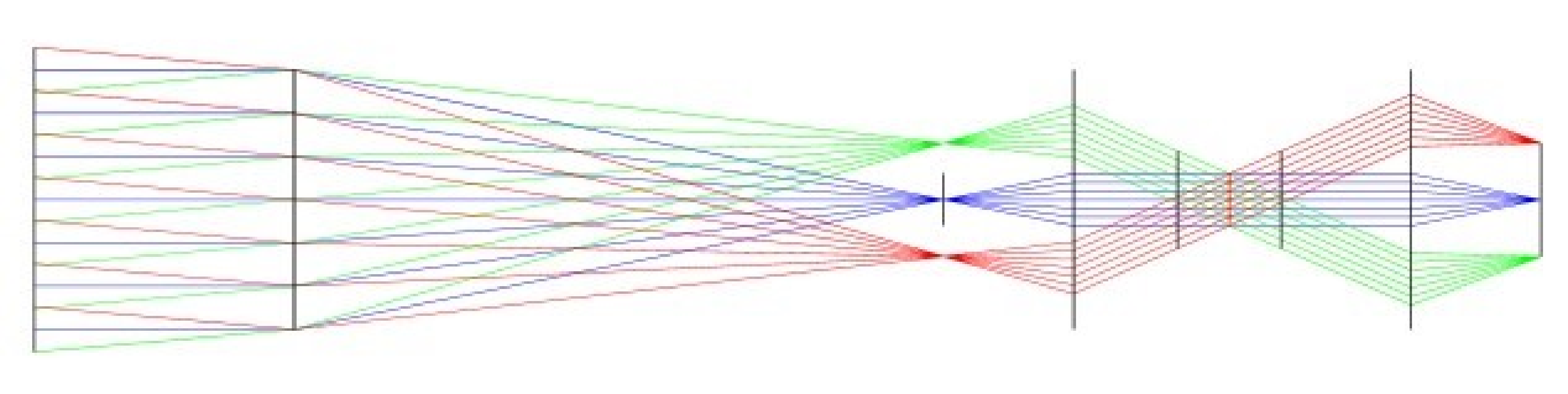
Adaptive Optics - 1

Requires:

- Characterization of the wavefront deformation with high speed !
- Almost on line application on deformable optics to compensate these deformations and restore the best achievable wavefront.
- Where can we applied this correction on an optical system ?

  → No incidence variation for the same object → Collimated beam

  → No field beam location dependence ! → Pupil plane



Telesc.Concept - 1

- ❖ Collecting power - High quality imaging - Pointing - Tracking
  Fast pointing (surveys) - Fast tracking (special objects)
- ❖ Refracting and Reflecting telescopes

Reflecting telescope designs

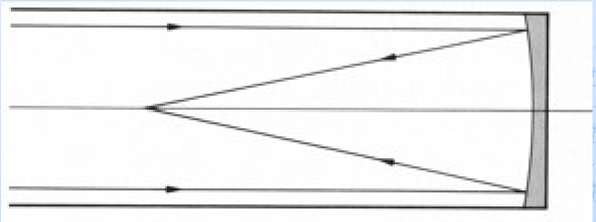
All M1 parabolic

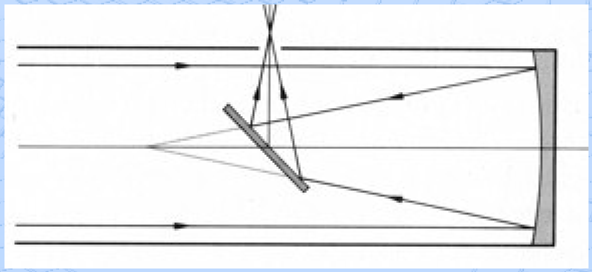
a) Prime focus !

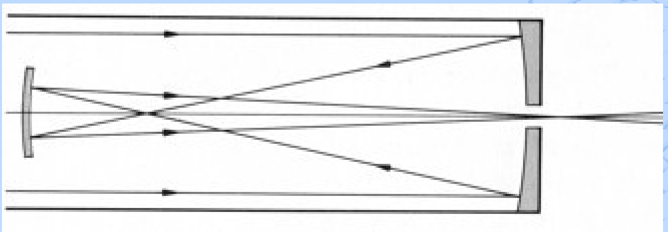
b) Newton

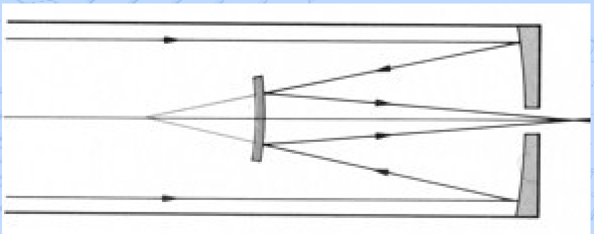
c) Gregorian M2 ellipsoid

d) Cassegrain M2 hyperboloid









Telesc.Concept - 2

Best image quality telescope with M_1 and M_2 conics (hyperb) with no SA

And Coma → Aplanat called Ritchey-Chretien type for Cassegrain design

Two mirrors design suffered from a field aberration limit !

→ The angular resolution is : $2.52 \cdot 10^5 \lambda / D$ (Airy $1.22 \lambda / D$) in arcsec (")

→ The plate scale is 206265 / f' ("/mm) - f' : focal of the telescope in mm

→ F/ratio is f' / D

❖ Catadioptric telescopes design:

- Schmidt – Schmidt Cassegrain - Maksutov ….

❖ Multi-mirror telescopes:

- ≥ 3 mirrors → large field anastigmatic telescope → ELT solution:

3 mirrors + 2 adaptive mirrors to compensate turbulences and errors

Telesc.Concept - 3

Ritchey-Chretien : NTT type D 3500mm, M1 and M2 asphericics

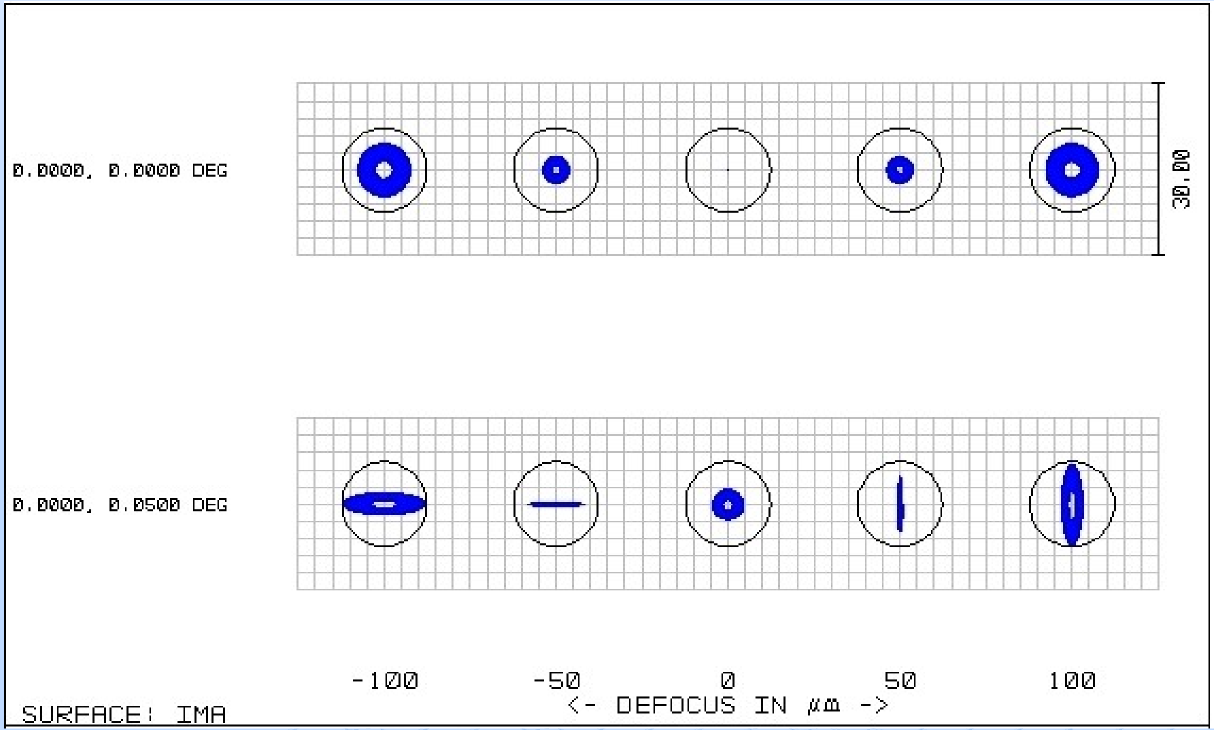
NTT - F/11 → f' = 38500mm → Scale = 5.36 "/mm or 0.187mm/"

Spot diagram showing residual aberration of 2 mirrors Telescopes

On axis

Field

3'



Astigmatism

Telesc.Concept - 4

Telescope Mounts:

- Classical equatorial mount :
  - One axis parallel to the earth axis, the other perpendicular.
  - “Old” generation for large telescope > 3m, still used for smaller one
  - Advantages: simpler to control (one axis tracking)
  - Inconvenient: generate large structures to sustain the telescope
  - Only one focus available on Cassegrain (could be prime focus)
- **Alt-Az Mount**:
  - Require tracking on both axis and Adapter rotation (field rotation)
  - All new telescope generation done that way → simplest structure
  - Multi foci possible (Cassegrain and Nasmyth)

Instr.Concept - 1

Spectrograph Instrument Concepts:

→ Dispersive element (prism, grating, grism) → Strict Condition →
no incidence angle variation from the same object point
Requires then a collimated beam → a Collimator and Camera to focus the different colored images of the star object point.
The principal elements forming a spectrograph are then:
The collimator, The dispersive element, The camera and The detector

An additional element is also fundamental to ensure a defined Δλ width relative to the detector "pixel" size. → the entrance slit (w)

- + : seeing independent if slit width < seeing disk (ω), fixed or adjustable Δλ with variable slit width,
- - : Slit losses → Image Slicer

Instr.Concept - 2

Spectrograph Mounted on a Telescope:

The Spectral Resolving Power R: $R = \lambda/\delta\lambda$ rewritted as

$$R = \lambda \times \frac{Angular\ Dispersion}{Seeing\ or\ Slit\ Width\ ('')} \times \frac{Collimator\ \phi}{Aperture\ Stop\ \phi}$$

Two Cases: Seeing or Slit width limited AND $\delta\lambda$ against Nyquist Criteria

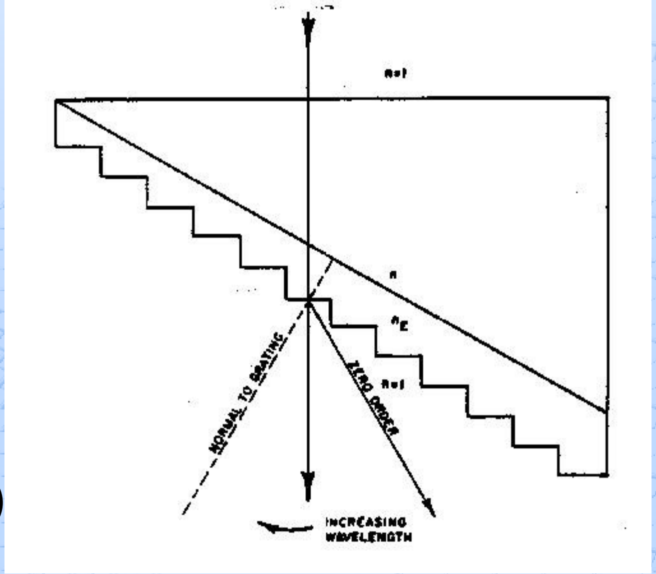
- If ASϕ increase, R decrease !!! (plate scale effect on slit, > light only)
- If ASϕ increase, we must increase the Collimator ϕ to keep R.
- For a fixed Collimator and AS ϕ the seeing or slit width in arcsec will increase R → Adaptive Optics
- Adding the Diffraction Limit effects the resolution is far beyond the theoretically possible one at visible light on ground based telescope.

Instr.Concept - 3

Grism: Addition of a prism with a grating (ruled or Volume Phase Holographic)

Can be used in transmission or even in reflection (immersion grism)

High efficiency
Dispersion with λ_0 un-deviated
Grating zero order falling out of axis !!
Dispersion related to the prism apex angle, its refraction index and the grating ruling.
Max efficiency when prism angle is equal to the blaze angle of the grating. (angle between grating surface and groove surface.)

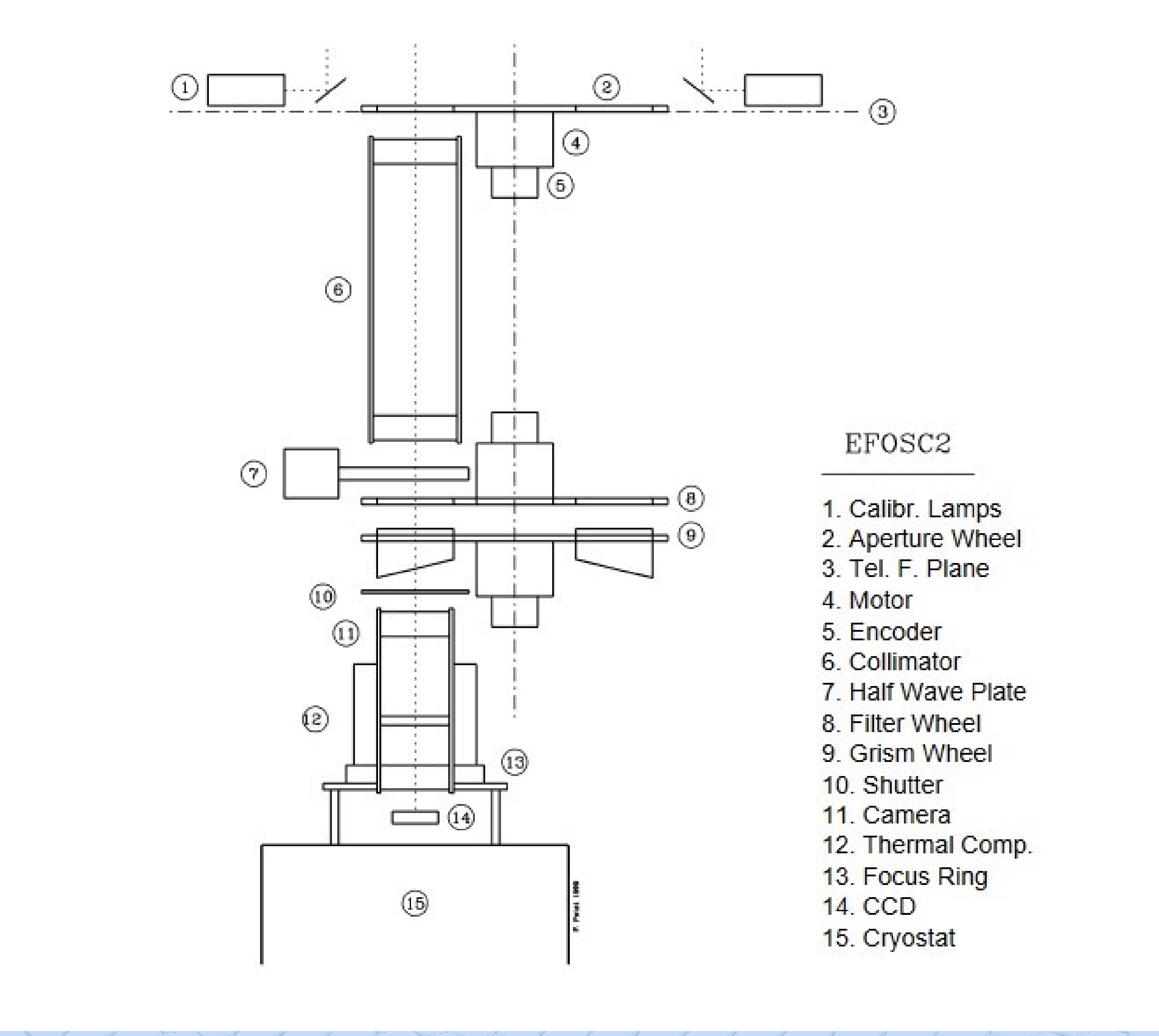


Instr.Concept - 4

EFOSC:

0.12”/pixels
0.24”/Nyquist
4’ x 4’ field imaging
380-1100 nm

Allow:
Imaging
Polarimetry
Spectro
Spect/polar.
Coronography



Instr.Concept - 5

Instrument Calibrations : Mandatory

- Detector sensitivity, linearity, ….
  - Dark exposures, Detector Flat Field, Fringes ….
- Instrument Relative Efficiency versus field : (vignetting corrections)
  - Flat field correction (white source lamps or sky before sunset)
- Instrument Field Image Quality
  - Complex .. the full telescope/instrument must be check
- Instrument Calibration on wavelength
  - Use of spectral lamps (several type according dispersion)
  - Simultaneous calibration for high precision
- Instrument Calibration on Polarimetry
  - Use standards stars or sky linear polarization or added polarizer during specific calibration runs
- Instrument Distortion calibration (astrometry)
  - Use pinhole mask to image the distortion effect,
  - check on known stellar field by image shift.