OPTICS Concepts related to Astronomy
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: $n$
  $n = \frac{\text{light speed in vacuum}}{\text{light speed in medium}}$

Speed/medium dependence
- Refraction (Lens application)
- Chromatism (2\text{nd} effect !!)
The Ray and the Wavefront:

Very important concept used in several optics topics.

Plane Wav.

Wavefront Propagation
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**.
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
Example with more lenses

Related effect → Vignetting
Another important parameter → F/Number

F/# = F / D
(F: focal, D: aperture diameter)
Optics cannot deliver perfectly stigmatic images...

And the departure from ideal conditions is called: Aberrations

- mainly classified in two groups depending on or not of the wavelength
  - Directly related to the refraction law reality (w/o approximation)
    \[ \text{Snell: } n_i \sin i = n_t \sin t \quad \& \quad i = r \]
    
    - \( i \) Incidence - \( t \) Transmitted - \( r \) Reflected
  - Chromatics additional effect on refraction
First order aberration:
- wavefront tilt ($\sim \sigma \rho$)
- defocus ($\sim \rho^2$)

Third order aberrations:
- **SA** - Spherical aberration ($\sim \rho^4$) → $\sigma$ independent!
- Field curvature ($\sim \rho^2\sigma^2$)
- Coma ($\sim \sigma \rho^3$) → linearly $\sigma$ dependent!
- Distorsion ($\sim \sigma^3 \rho$) → cube $\sigma^3$ dependent!
- **Astigmatism** ($\sim \sigma^2 \rho^2$) → square $\sigma^2$ dependent!
Aberrations on Telescope optic beam!

SA effect

Astigmatism

Coma
• **The chromatic aberration:**
  
  Refraction dependent on wavelength.

Axial and lateral chromatism effects
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
Polarization:
Linear / Circular

Polarizers:
Dichroism, Reflection,
Bi-refringence, Scatter

Wollaston prism, Retarders
Interferences:
Interferences/Diffraction:

Single slit: minima at $m \frac{\lambda}{b}$
b slit width $\rightarrow$ Diffraction

Double slit: minima at $m \frac{\lambda}{a}$
& at $m \frac{\lambda}{b}$, a slit separation
$\rightarrow$ Interferences

➢ Circular aperture effect: **The Airy disk**

The first dark ring radius is $r = 1.22 \frac{f \lambda}{d}$ (d diameter of Aperture Stop)

$\rightarrow$ Two telescopes of 4 and 8m will resolve an angle separation of $3.1 \times 10^{-2}$ and $1.6 \times 10^{-2}$ arcsec
Diffraction/Interference/Coherence 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
Optical Path Difference: **OPD**.

Interference on air wedge

- **Constructive interference**: Reflected waves in phase
- **Destructive interference**: Reflected waves 180° out of phase

\[ \text{Path length difference} = \begin{cases} \text{odd multiple of } \lambda/2, & \text{for constructive interference} \\ \text{even multiple of } \lambda/2, & \text{for destructive interference} \end{cases} \]

**VLT interference**

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A. Gilliotte – Optics / Seon 2020
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 $\phi$ related to $D$. For an optics $D > r_0$ the airy disk $\phi$ 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 $r_0 \sim 25 \text{ cm} \text{ at } 500\text{nm}$ then $148 \text{ cm} \text{ at } 2.2\mu\text{m}$ and $910\text{ cm} \text{ at } 10\mu\text{m}$

An $r_0$ of $25\text{ cm} \sim$ to $0.4$ arcsec seeing at $500\text{nm}$

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

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

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

The shorter it is, faster should be the corrective actions

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

$\rightarrow$ The Isoplanetic Angle $\Theta$: Field angle with acceptable $\sim r_0$
Turbulence - 3

Very short exposures

D/r₀ ratio = 2  \hspace{1cm} \text{ratio} = 7 \hspace{1cm} \text{ratio} = 20

With longer exposures the 3 images will be equivalent to the ω disk

Very short exposures

slow motion (1/40 of normal)
Ratio D/r₀ ~ 10
Bad seeing
Additional turbulence local effects to the telescope:

- 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 Antarctica)

- 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
Best image quality telescope with $M_1$ and $M_2$ conics (hyperb) with no SA and Coma $\rightarrow$ Aplanat called Ritchey-Chretien type for Cassegrain design

Two mirrors design suffered from a field aberration limit!

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

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

$\rightarrow$ F/ratio is $f' / D$

❖ Catadioptric telescopes design:

• Schmidt – Schmidt Cassegrain - Maksutov ….

❖ Multi-mirror telescopes:

• $\geq 3$ mirrors $\rightarrow$ large field anastigmatic telescope $\rightarrow$ ELT solution:

  3 mirrors + 2 adaptive mirrors to compensate turbulences and errors
Ritchey-Chretien: NTT type D 3500mm, M1 and M2 aspherics

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
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
Spectrograph Mounted on a Telescope:

The Spectral Resolving Power \( R \):
\[
R = \frac{\lambda}{\delta\lambda}
\]
rewritten as

\[
R = \lambda \times \frac{\text{Angular Dispersion}}{\text{Seeing or Slit Width (\"\)}} \times \frac{\text{Collimator } \phi}{\text{Aperture Stop } \phi}
\]

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

- If AS\( \phi \) increase, \( R \) decrease !!! (plate scale effect on slit, > light only)
- If AS\( \phi \) increase, we must increase the Collimator \( \phi \) to keep \( R \).
- For a fixed Collimator and AS \( \phi \) the seeing or slit width in arcsec will increase \( R \rightarrow \) Adaptive Optics
- Adding the Diffraction Limit effects the resolution is far beyond the theoretically possible one at visible light on ground based telescope.
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 $\lambda_0$ 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.)
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.