Optical/IR Observational Astronomy

Telescopes I: Optical Principles

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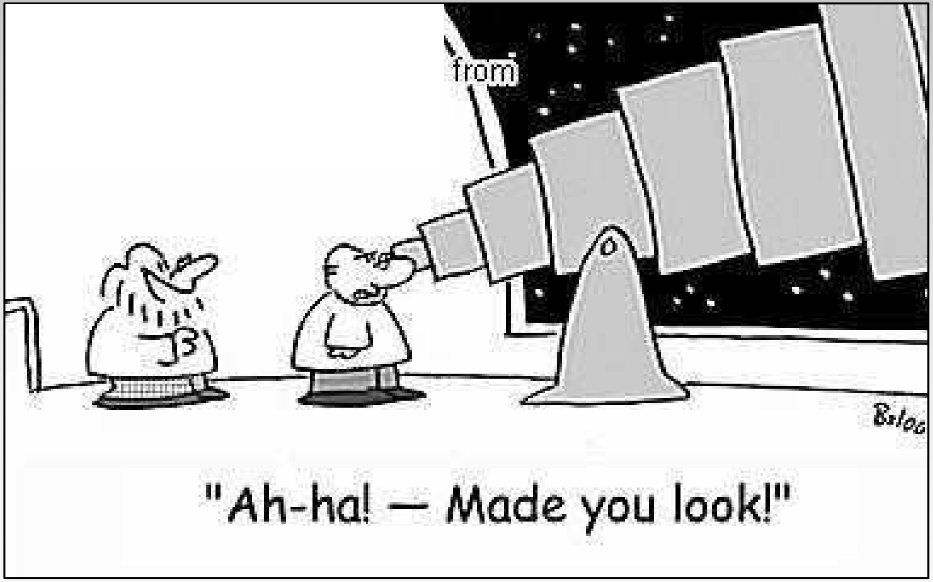
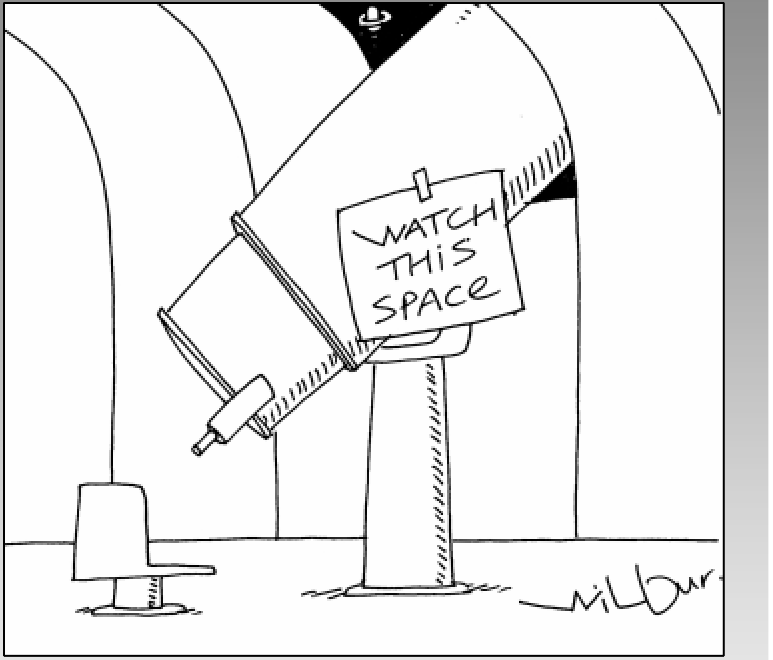
What Do Telescopes Do?

- They collect light
- They form images of distant objects
- The images are analyzed by instruments
  - The human eye
  - Photographic plates/film
  - Digital detectors (e.g. CCDs)



"Ah-ha! — Made you look!"



Key parameters for an astronomical telescope:

- **Light gathering power**

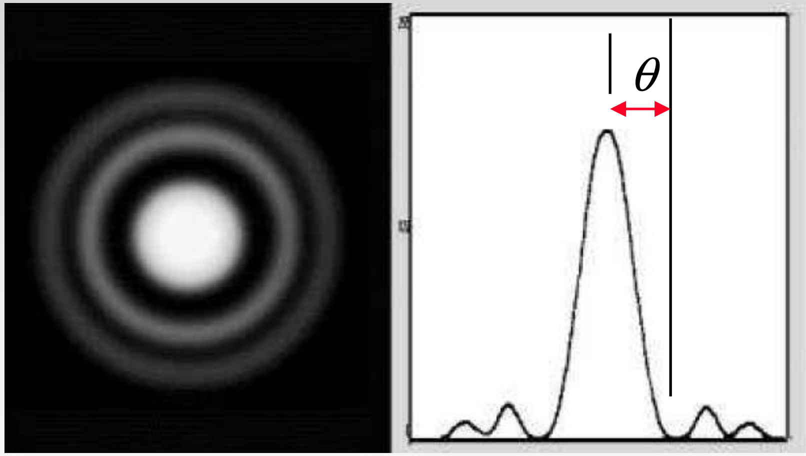
  Determined by the *area* of the collecting element (objective lens of mirror)

  $\propto$ *telescope diameter*^{2}

- **Resolution**

  Measure of the how much fine detail can be seen in an image

  $\propto$ *telescope diameter (a)*



$$\theta = 1.22 \frac{\lambda}{a}$$

Key parameters for an astronomical telescope:

- **Intrinsic image quality**

  Determined by the *figure* of the individual optical elements (how close they are to their ideal shape) and how well they are aligned.

- **Field of view (FoV)**

  Determined by the optical design. Usually expressed as field *diameter.* Information content ∝ area of FoV ∝ diameter of FoV^2

- **Throughput**

  How efficiently photons are delivered to a focus. Determined by the transmissiveness of lenses and the reflectivity of mirrors.

- **Tracking & pointing capability**

  This determines overall performance in terms of *observational efficiency* and how well image quality is retained during an observation.

Other considerations:

- **Instruments**

  A telescope is only as good as the instruments that are available on it.

- **Telescope & building design**

  This can greatly affect the delivered image quality.

  Local "seeing" effects by poorly design telescope tube, dome or building can compromise the optical performance (blurring effects of air currents).

- **The *etendue* of a telescope**

  This is a *<u>figure of merit</u>* parameter related to both the light collecting area (*A*) and FoV (*Ω*)*:*

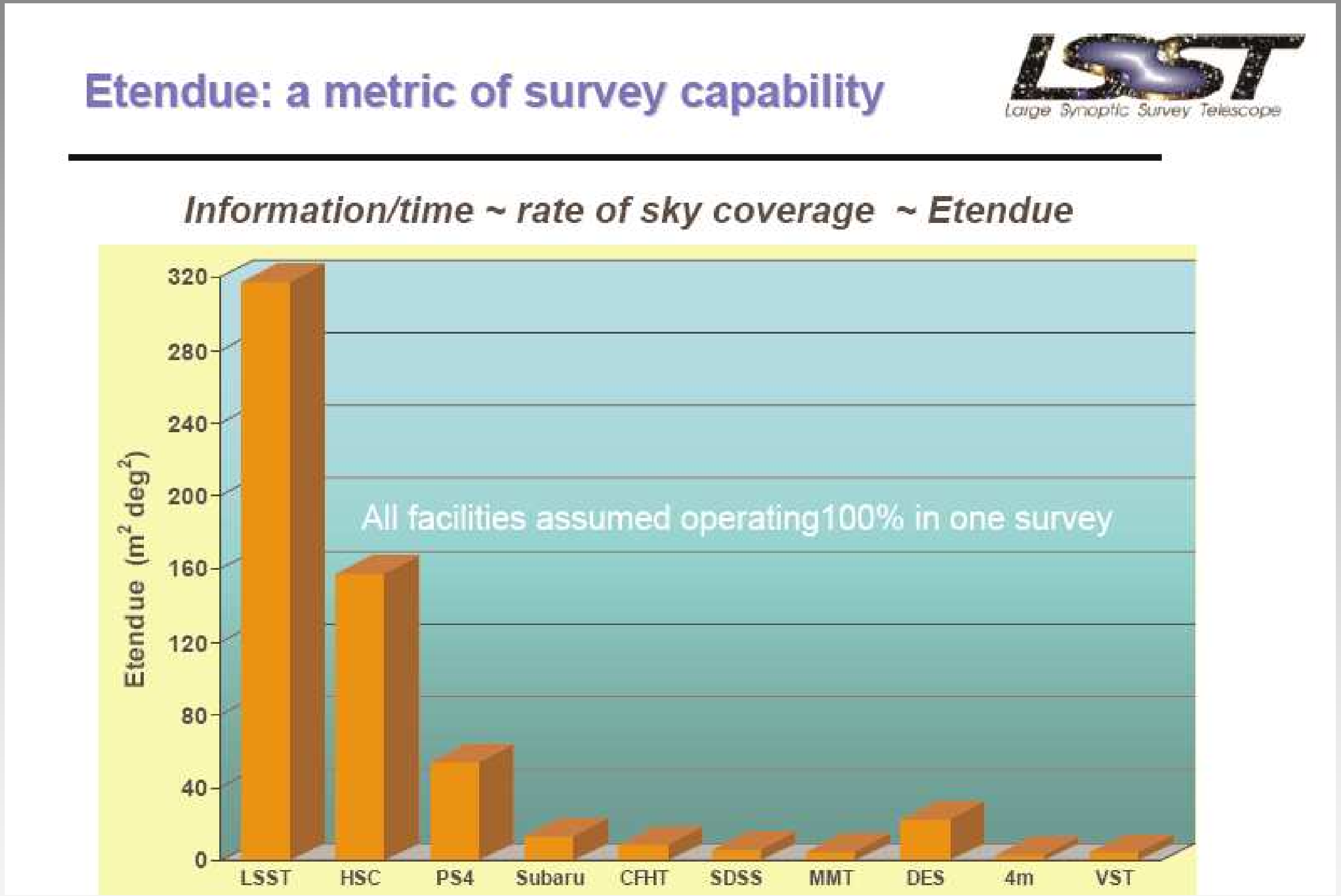
$$E = A \,.\, \Omega$$

[N.B. this parameter does not factor in the resolving power of the telescope, another important parameter]

Optical/IR Observational Astronomy

Telescopes I: Optical Principles

The Large Synoptic Survey Telescope

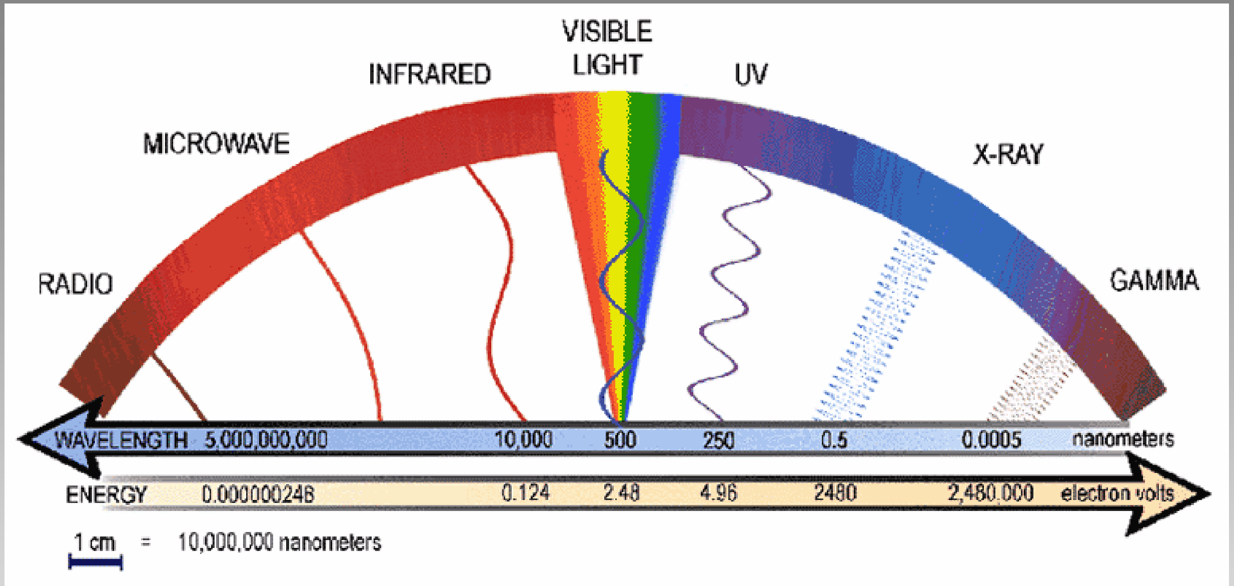


Etendue: a metric of survey capability

Information/time ~ rate of sky coverage ~ Etendue

Homework: calculate SALT's etendue

The Electromagnetic Spectrum



- **Visible – Ångstrom (Å). Traditional optical range unit (10^{-10} m)**
  - **Nanometre commonly used (10^{-9} m)**
- **Infrared – Micron (µm). Near infrared 1 – 5 µm (1µm = 10^{-6} m).**
- **Radio – mm “microwave”.**
- **Radio – cm. eg. 21cm line of neutral Hydrogen.**
- **Radio – Frequency/Hertz (Hz). eg. 21cm = 1420 MHz.**
- **X-ray, -ray – Energy (eV). eg. 1 keV = 2.4×10^{17} Hz = 12.4×10^{-10} m**

Ground-based Optical/IR Telescopes

All of them look through the blanket of the Earth's atmosphere.

So we need to take account of its effects:

- **Attenuation of light due to absorption effects**

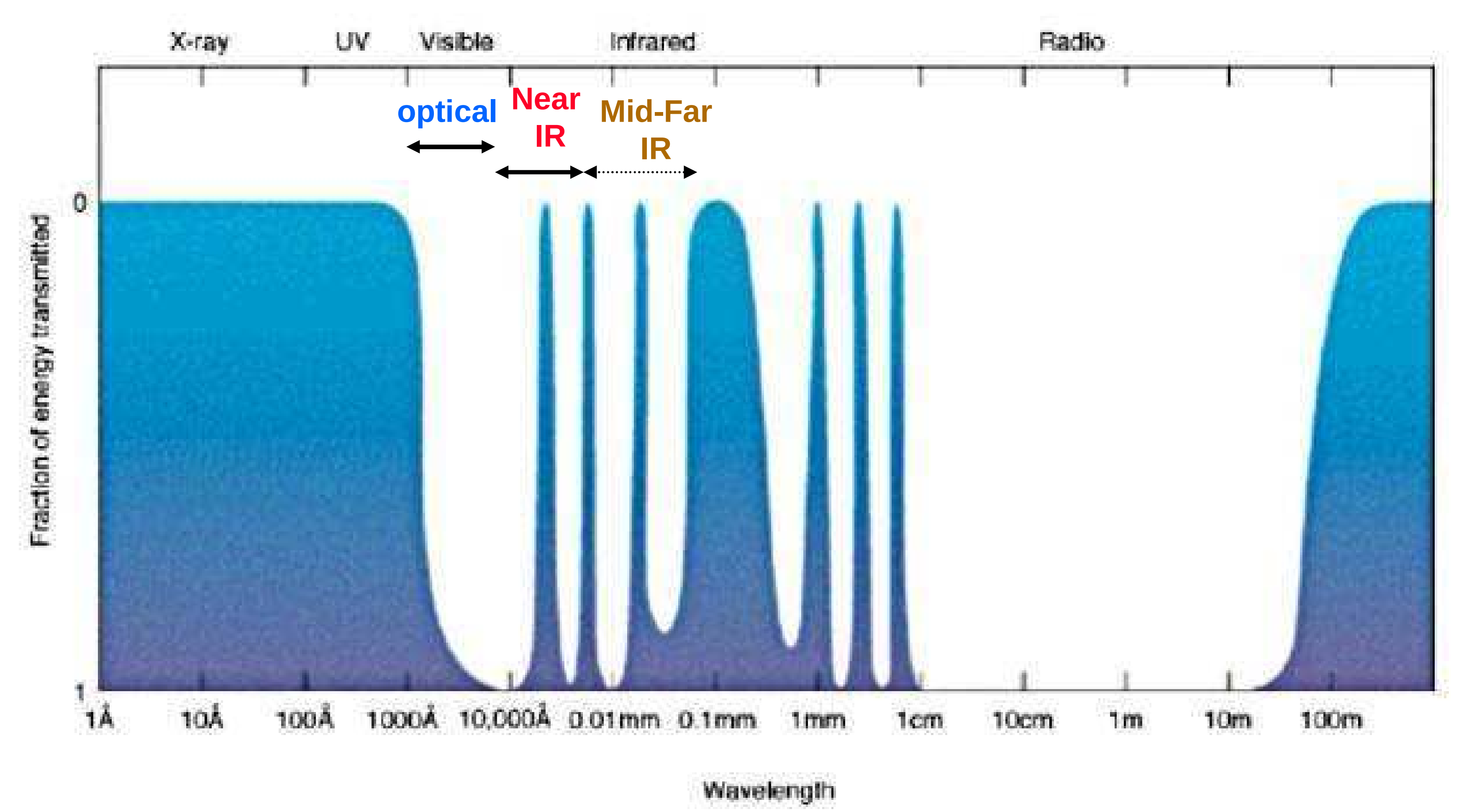
  - by atoms & molecules
- **Scattering of light**

  - by dust & aerosols
- **Emission**

  - from atoms & molecules excited by Solar radiation
- **Refraction & dispersion**
- **Wavefront perturbations causing optical aberrations of images**

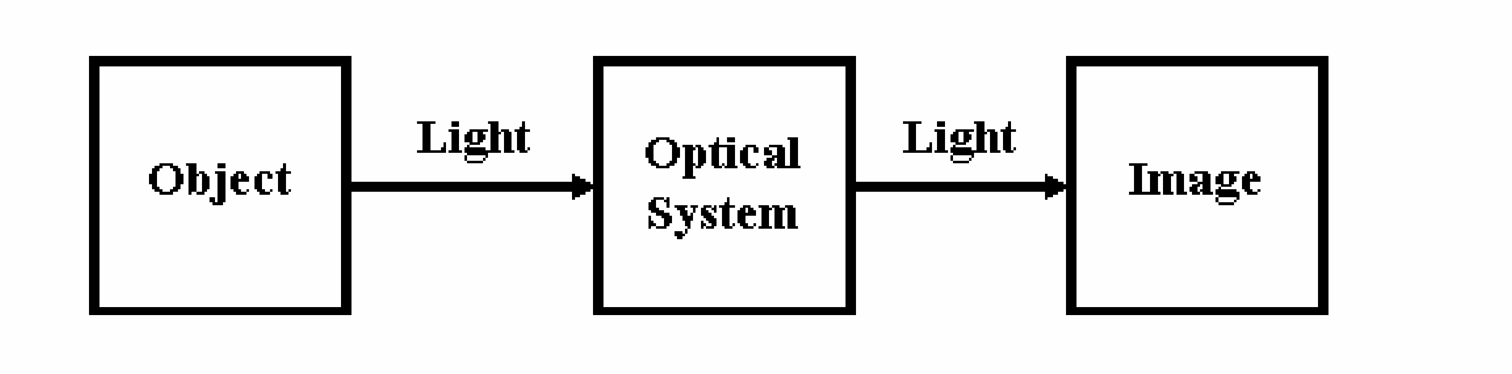
  - air has a wavelength dependent refractive index

- **Transmission of the Earth's atmosphere**

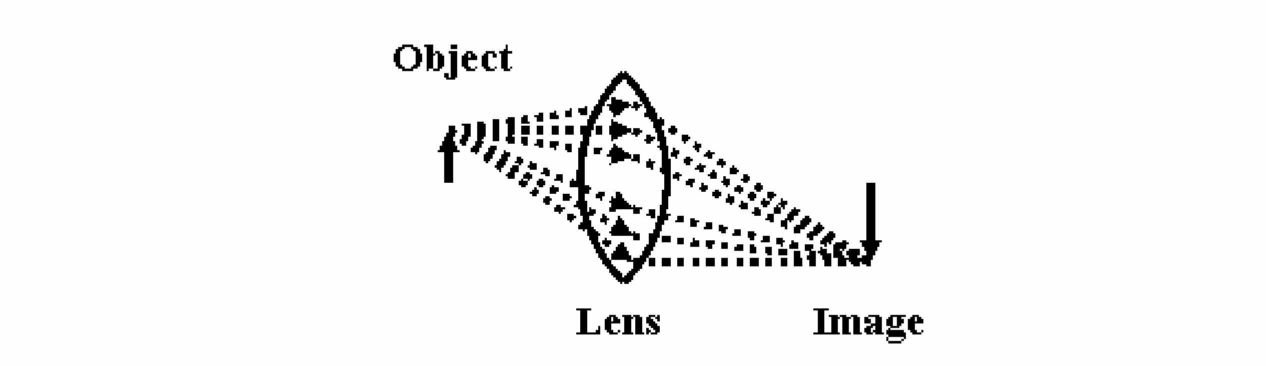


Telescope Optics

- What is a telescope system? With optics (lenses or mirrors) it produces an image of an object at a distance.

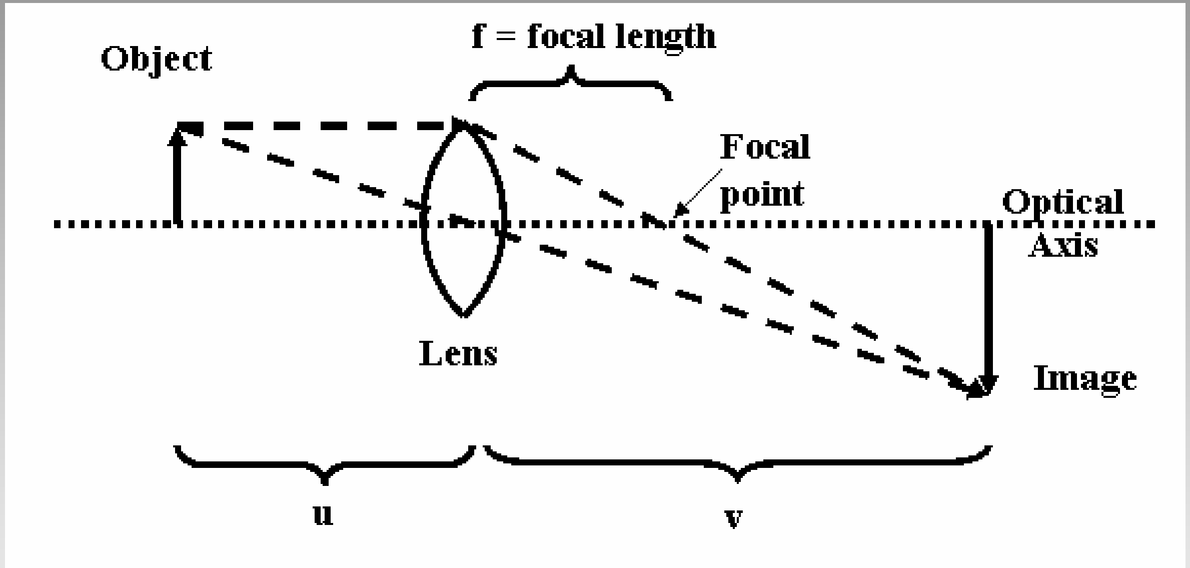


Object → Light → Optical System → Light → Image



Telescope Optics

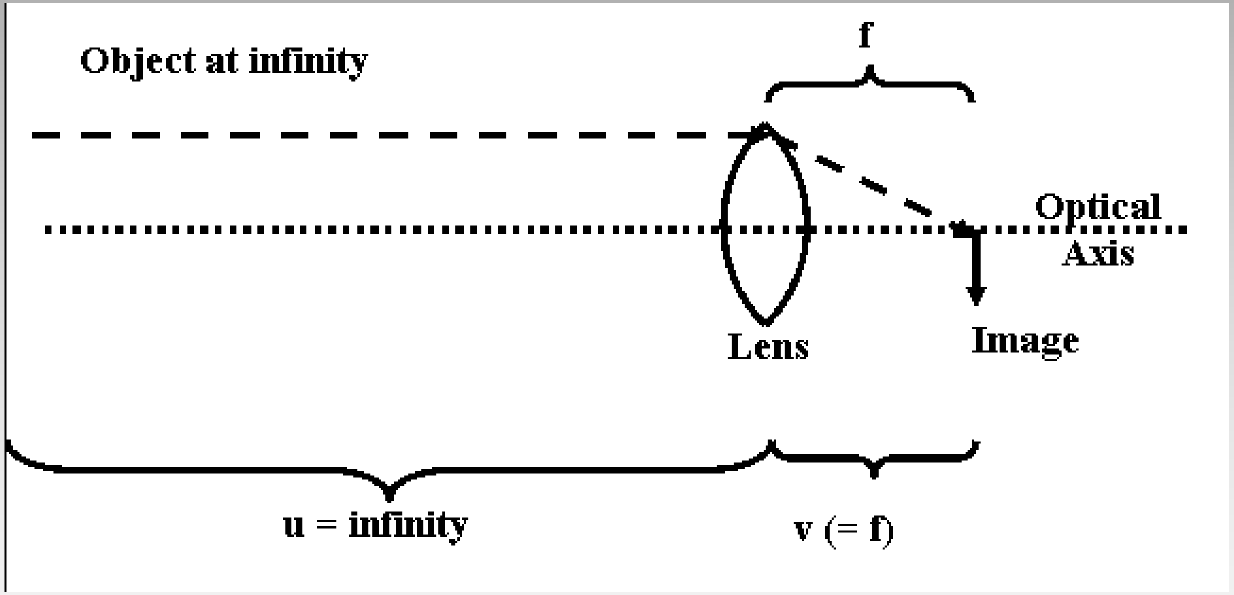
- Review basic knowledge of geometric optics



$$1/u + 1/v = 1/f$$

Telescope Optics

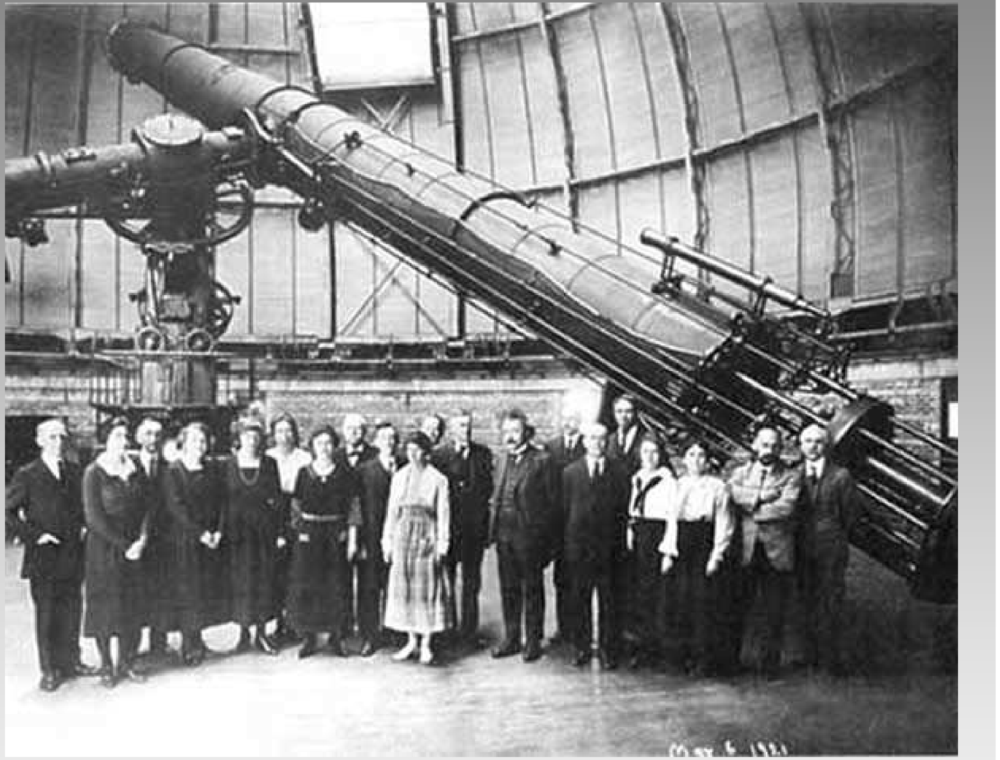
- For astronomical telescopes we can assume that the ‘object’ is at infinity ($u = \infty$)
- Example of a basic *refractor* using a *positive* lens (e.g. biconvex)



Telescope Optics

Refractors:

- **The lens has to be supported around the edge (like spectacles)**
- **As lenses become bigger (light grasp $\propto d^2$), the mass increased as the cube of the size ($m \propto d^3$)**
- **Supporting the lens became harder (bigger and more complex)**
- **Flexure (bending) of the lens itself cause 'figure' to change, resulting in optical *aberrations***
- **Largest refractor ever made is the Yerkes telescope in the US (1 m diameter)**

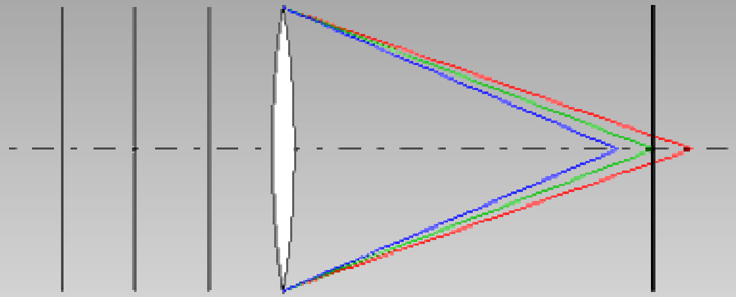


Yerkes refractor in 1895

Telescopes I: Optical Principles

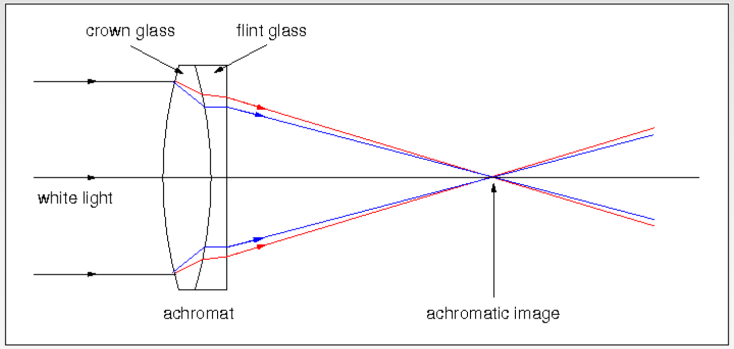
Refractors:

- **Lenses bend light to a focus through refraction**
- **As refraction is wavelength dependent, certain *chromatic* aberrations occur**



Different wavelengths brought to different foci

- **Some corrections for this can be done by combining lenses of varying refractive index**

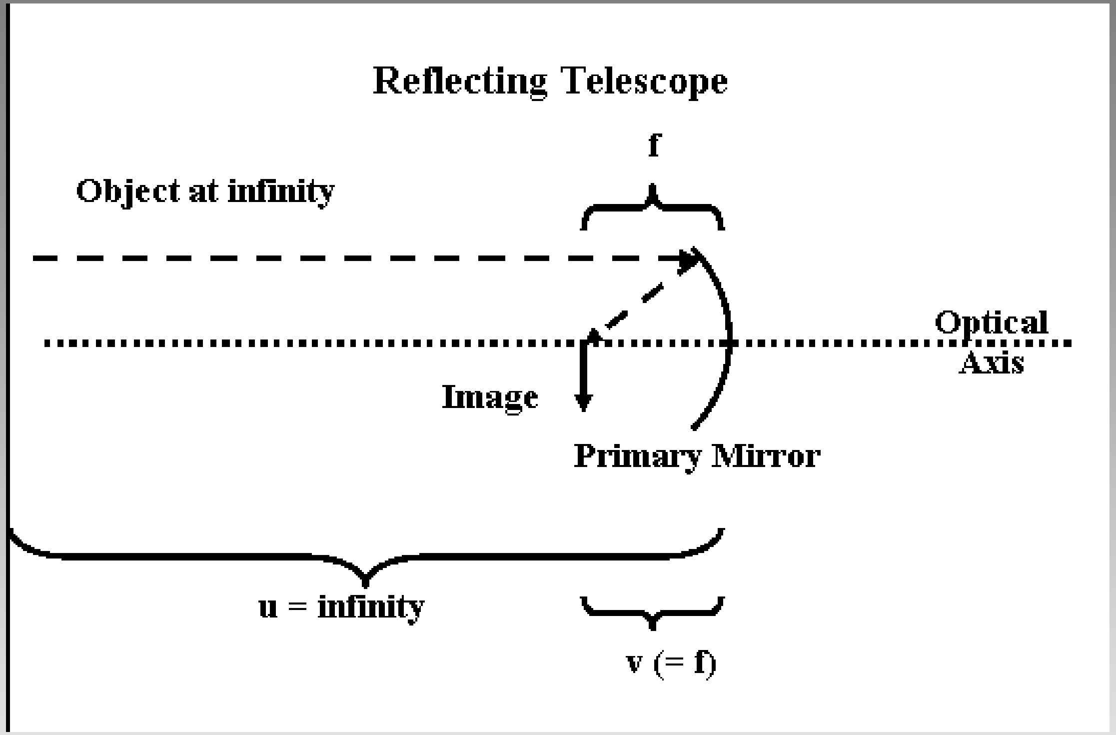


Correction achieved with achromat doublet

Yerkes today

Telescopes I: Optical Principles

Reflectors



- Reflection is *wavelength* independent
- Avoids *chromatic* effects
- Can support them from behind, so they can be *much bigger* than any lens (up to 8.3 m diameter current limit for single *monolithic* mirror)

Optical Aberrations

Departures from *ideal* image caused by *optical aberrations.*

- **Simple lens formula derived under the assumption of infinitely thin element and rays parallel to the optical axis (axis of symmetry)**
  - **This is called the *paraxial* case**
- **Next level of complexity allowed for small angles of incidence to real lens surface and refractive indices.**
  - **Rays are close to paraxial**
- **Off-axis effects were calculated with the assumption of small enough incidence angle such that the approximation $\sin\theta = \theta$ and $\cos\theta = 1$ is valid.**
- **This is referred to as *first order* or *Gaussian theory***

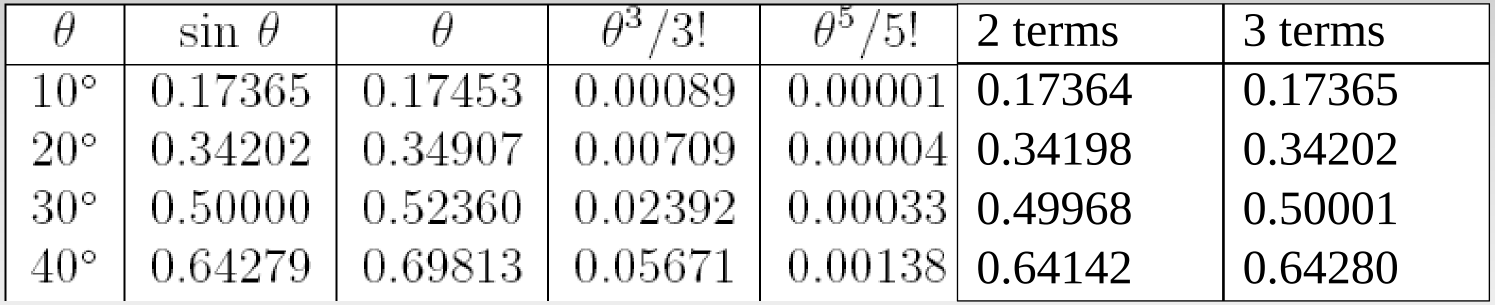
Optical Aberrations

To have a better approximation to reality:

- We abandon the approximation *sin* $\theta = \theta$
- Instead use the standard McClaurin expansion:

$$sin\ \theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} - \ldots\ldots$$

- This provides a much better approximation for higher incidence angles



θ	$\sin\theta$	θ	$\theta^3/3!$	$\theta^5/5!$	2 terms	3 terms
10°	0.17365	0.17453	0.00089	0.00001	0.17364	0.17365
20°	0.34202	0.34907	0.00709	0.00004	0.34198	0.34202
30°	0.50000	0.52360	0.02392	0.00033	0.49968	0.50001
40°	0.64279	0.69813	0.05671	0.00138	0.64142	0.64280

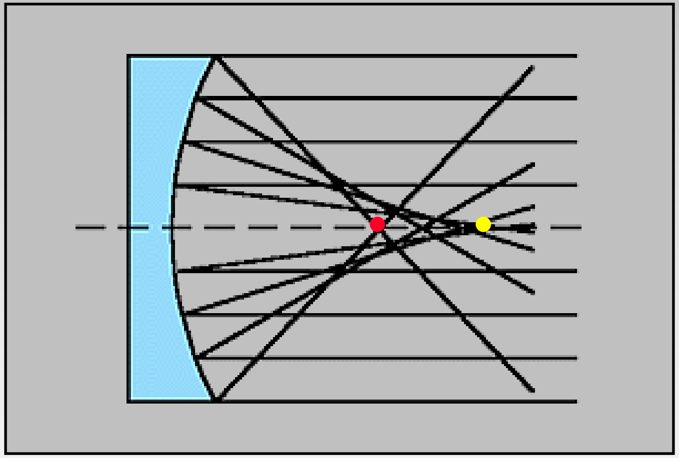
- Use of 2 terms is called *third order* (up to θ^3) and is used to define the Seidel aberrations

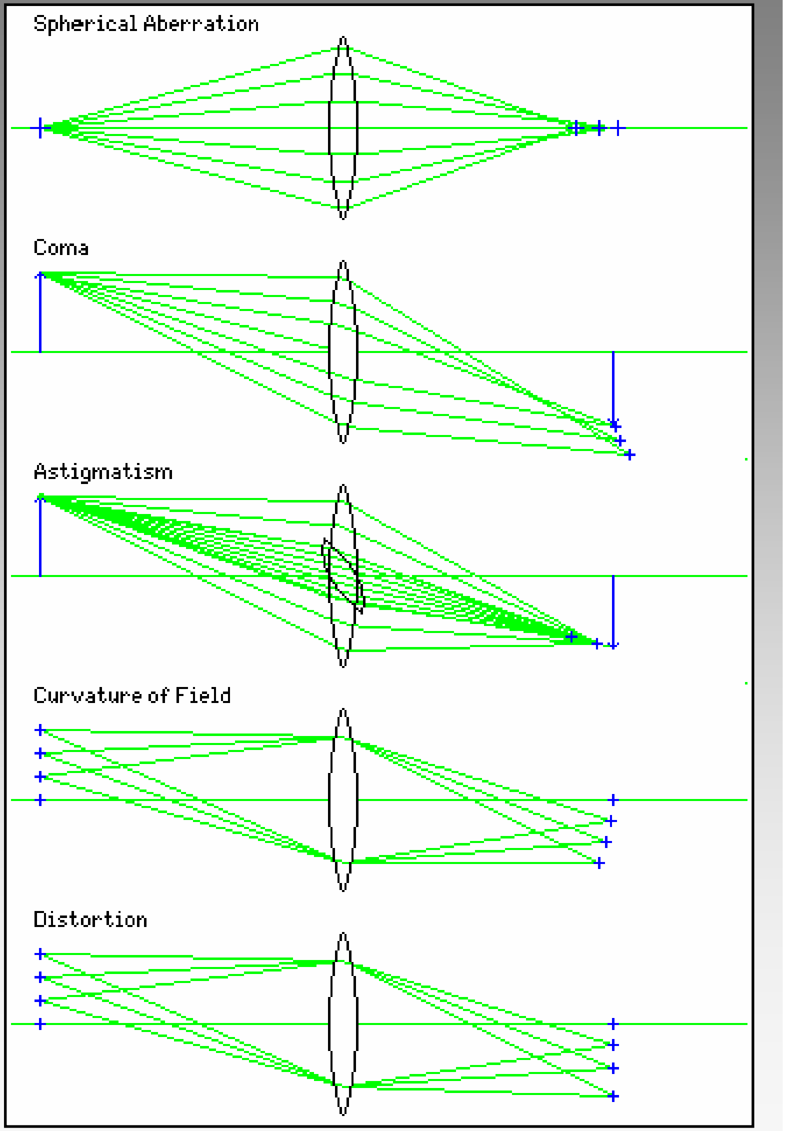
Optical Aberrations

The Seidel aberrations:

1. Spherical Aberration

Different focus points between paraxial (passing along optical axis) and marginal (furthest from optical axis) rays.





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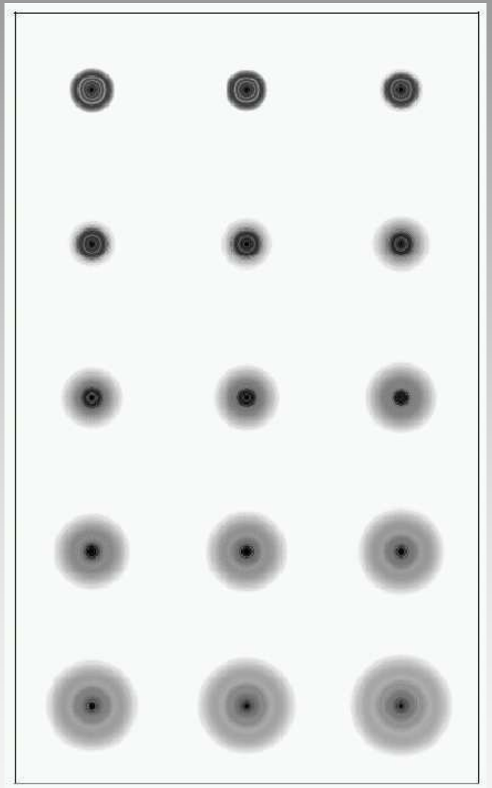
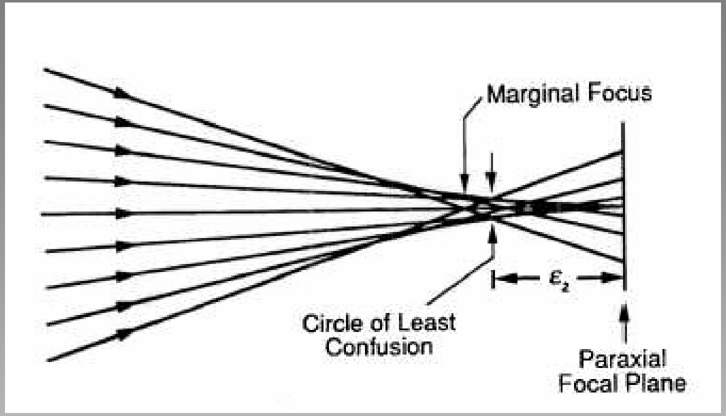
Telescopes I: Optical Principles

Optical Aberrations

1. Spherical Aberration

Different focus point





Spherical because a sphere images just like this.

- perfect image only of centre of curvature
- *any* optic (spherical or not) can show exhibit it
- ideal mirror to image on-axis object at ∞ is a *paraboloid* (as used in most telescope primary mirrors).

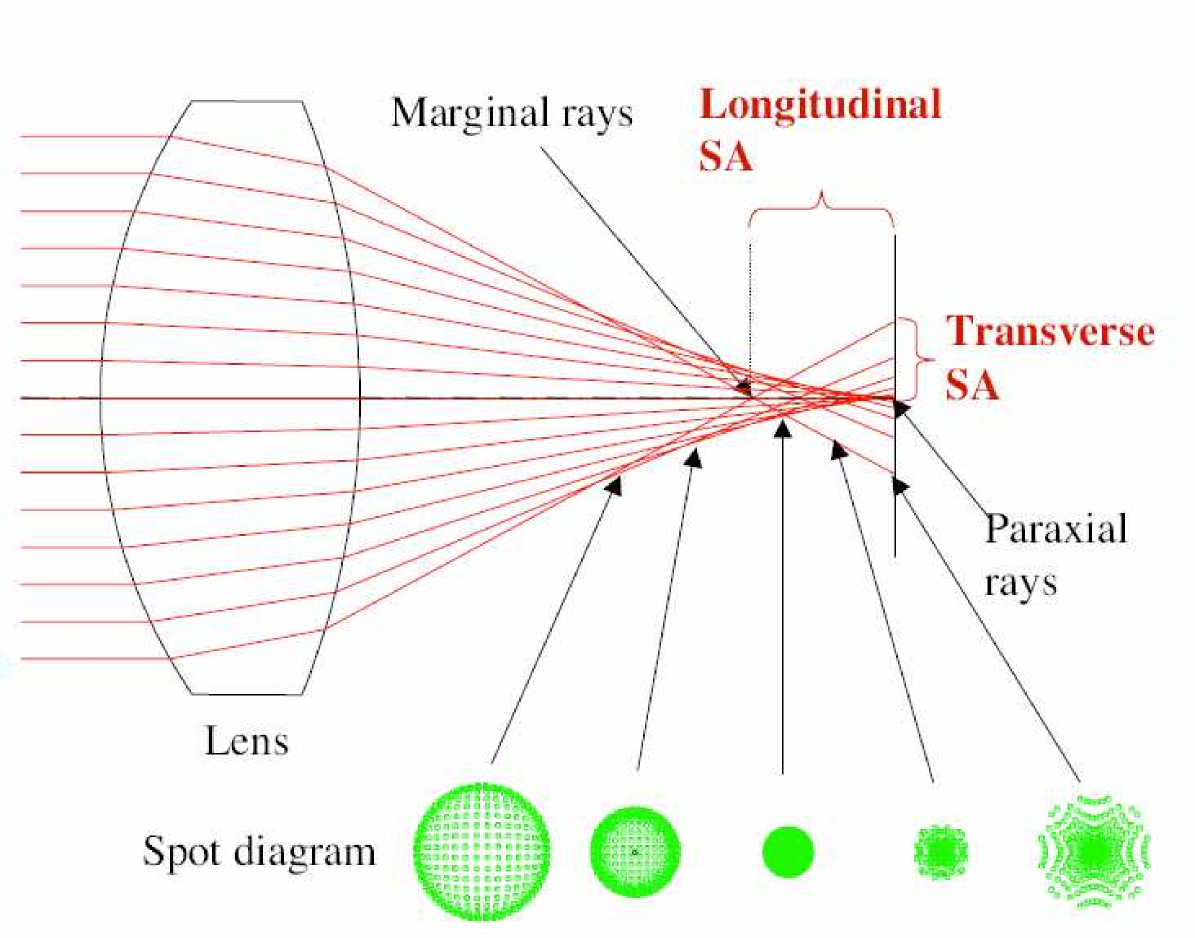
__SALT__

Since SALT is deliberately designed to have a *spherical primary mirror* it suffers from severe spherical aberration

- *circle of least confusion ~10 arcmin (1/3rd Lunar diameter)*

Optical Aberrations

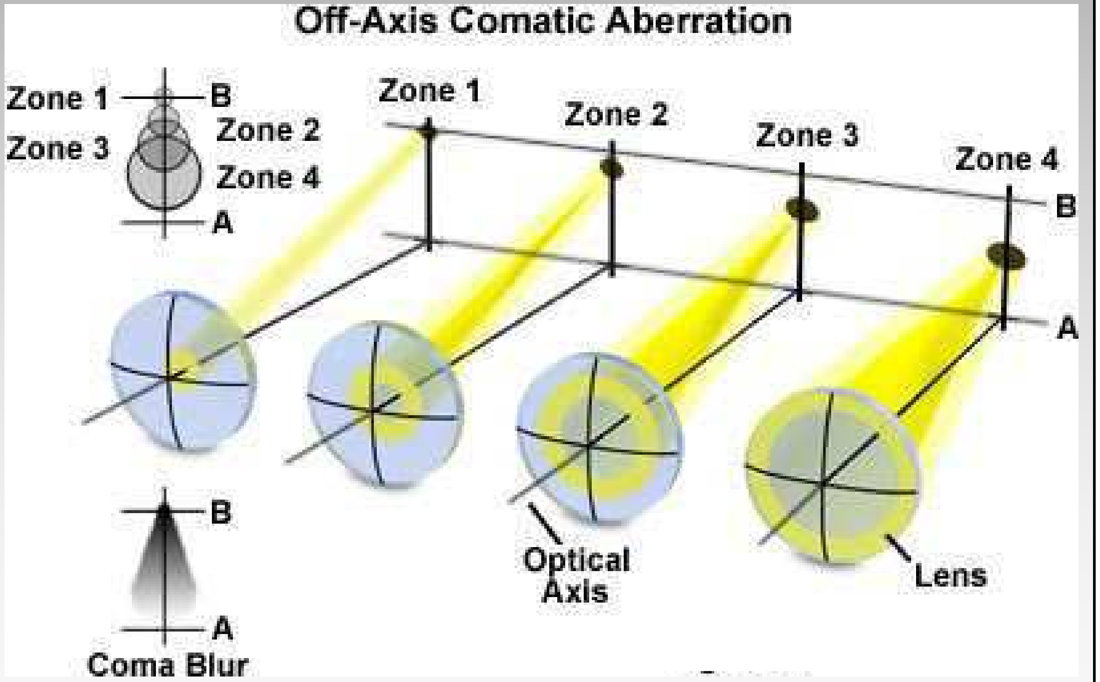
1. Spherical Aberration

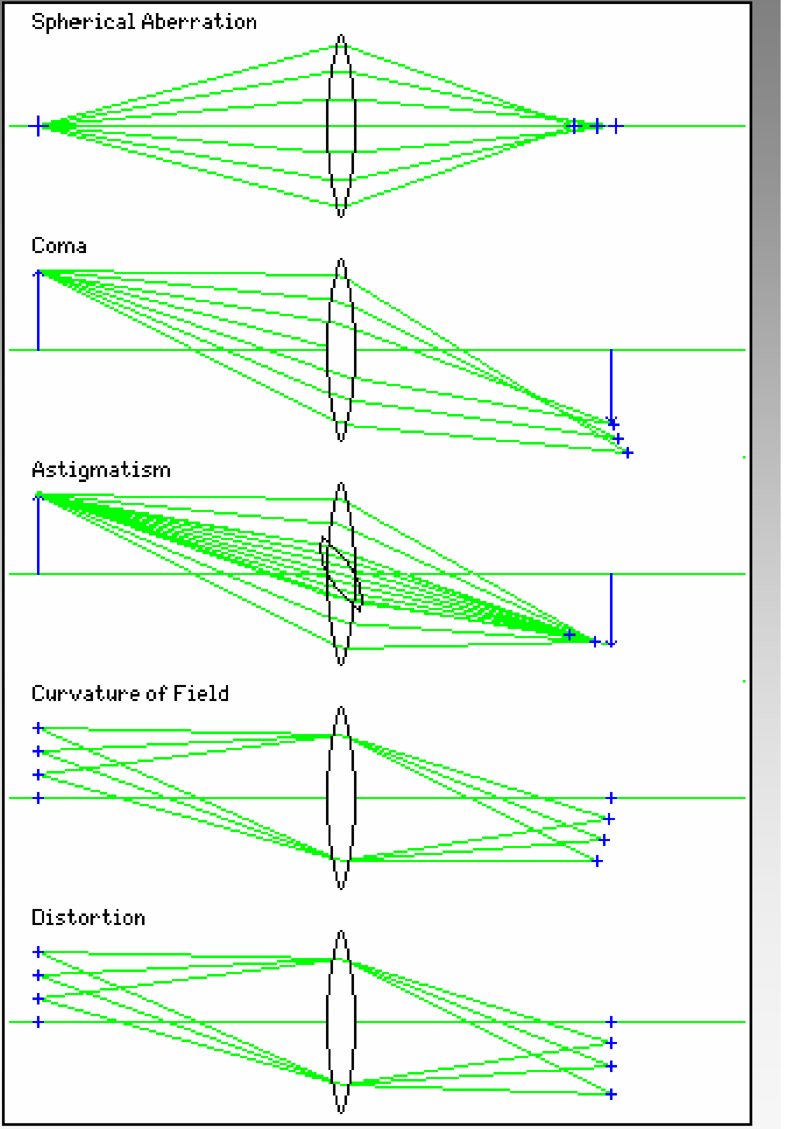


Optical Aberrations

2. Coma

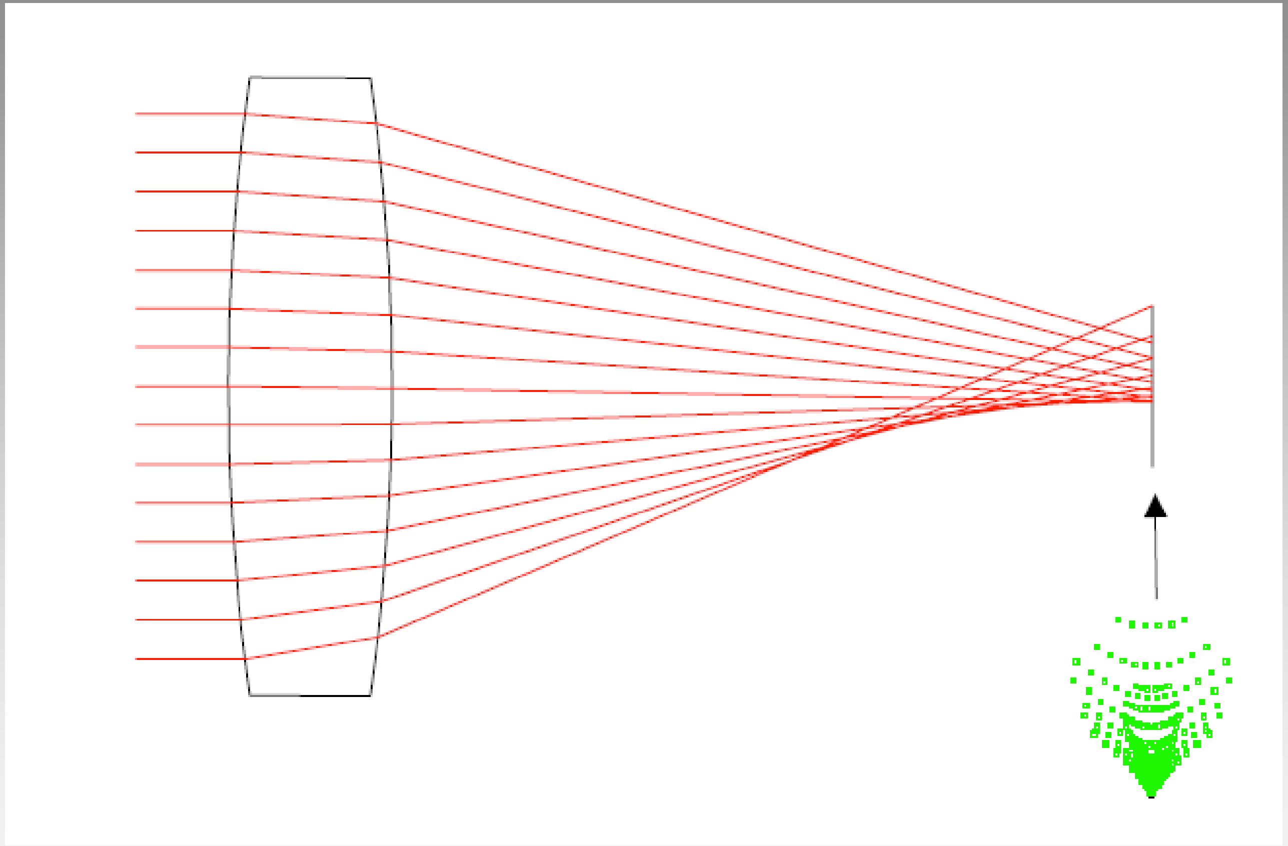
Distortion of *off-axis* images as a result of rays having different foci for marginal & paraxial rays.





Optical Aberrations

2. Coma



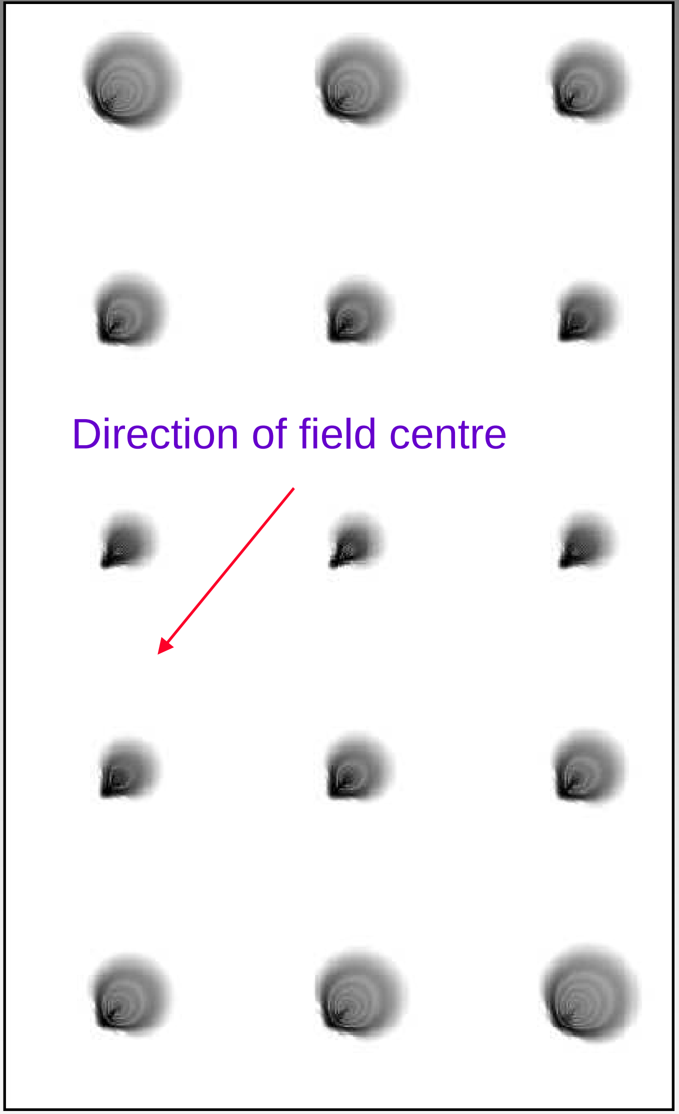
Optical Aberrations

2. Coma

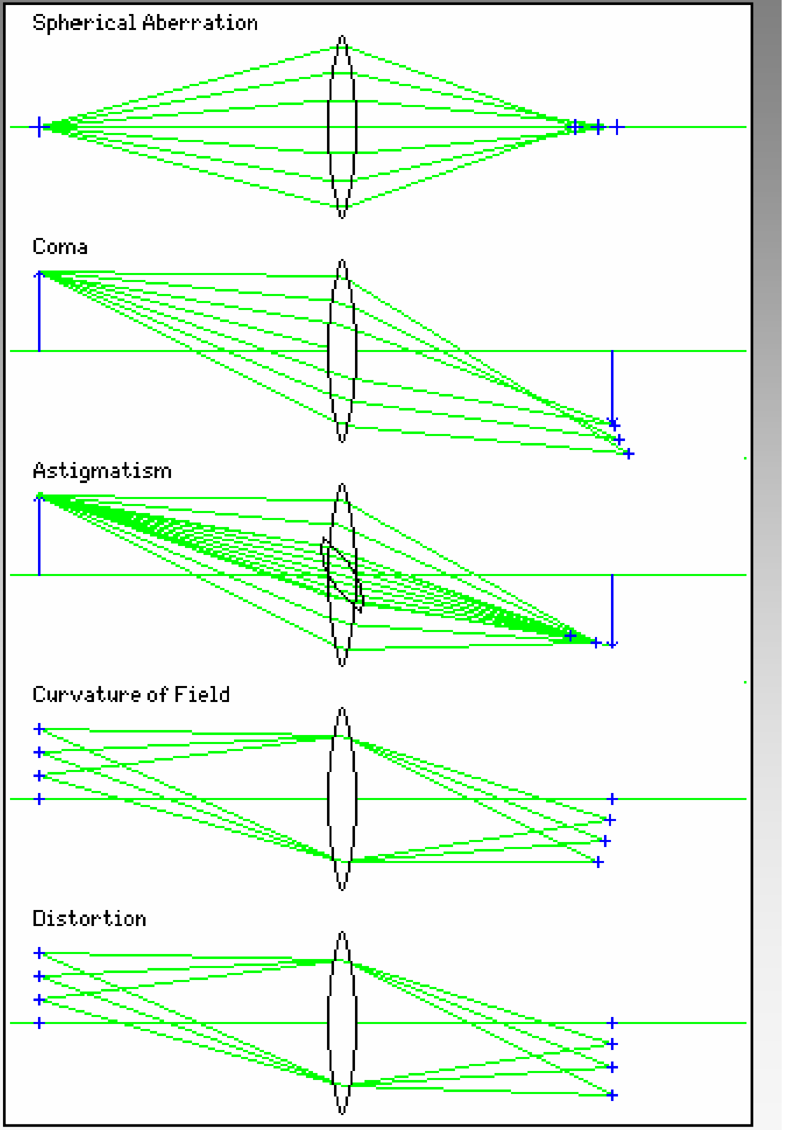
Image at a particular field position is produced by overlapping images produced by annular zones centred on the optical axis.

Because their angular displacement is a function of annulus size, the images are spread out along a radius vector to the field centre.

Called “coma” due to their comet-like appearance

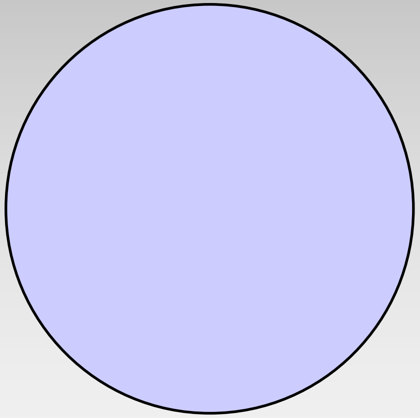


Optical Aberrations

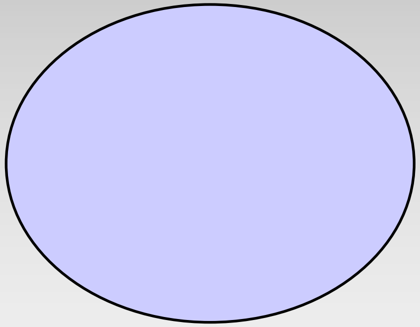


3. Astigmatism

- Another *off-axis* aberration produced by the varying “projection” of the surface of the optical element with off-set angle
- Hence changing incidence geometry with field angle which itself changes with respect to the elements orientation.



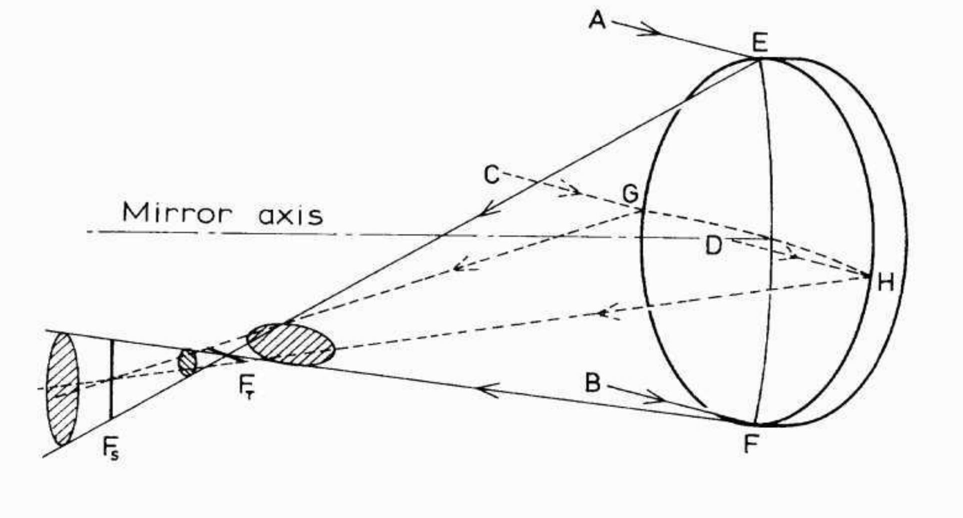
On-axis projection of optic



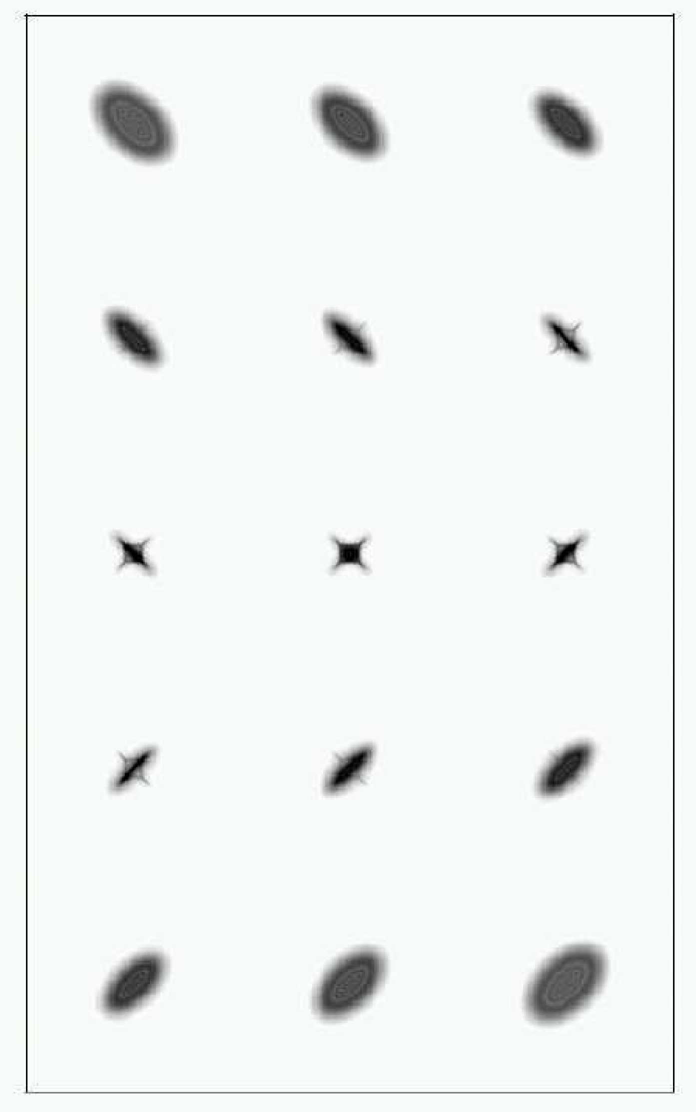
Off-axis projection of optic (up-down)

Optical Aberrations

3. Astigmatism



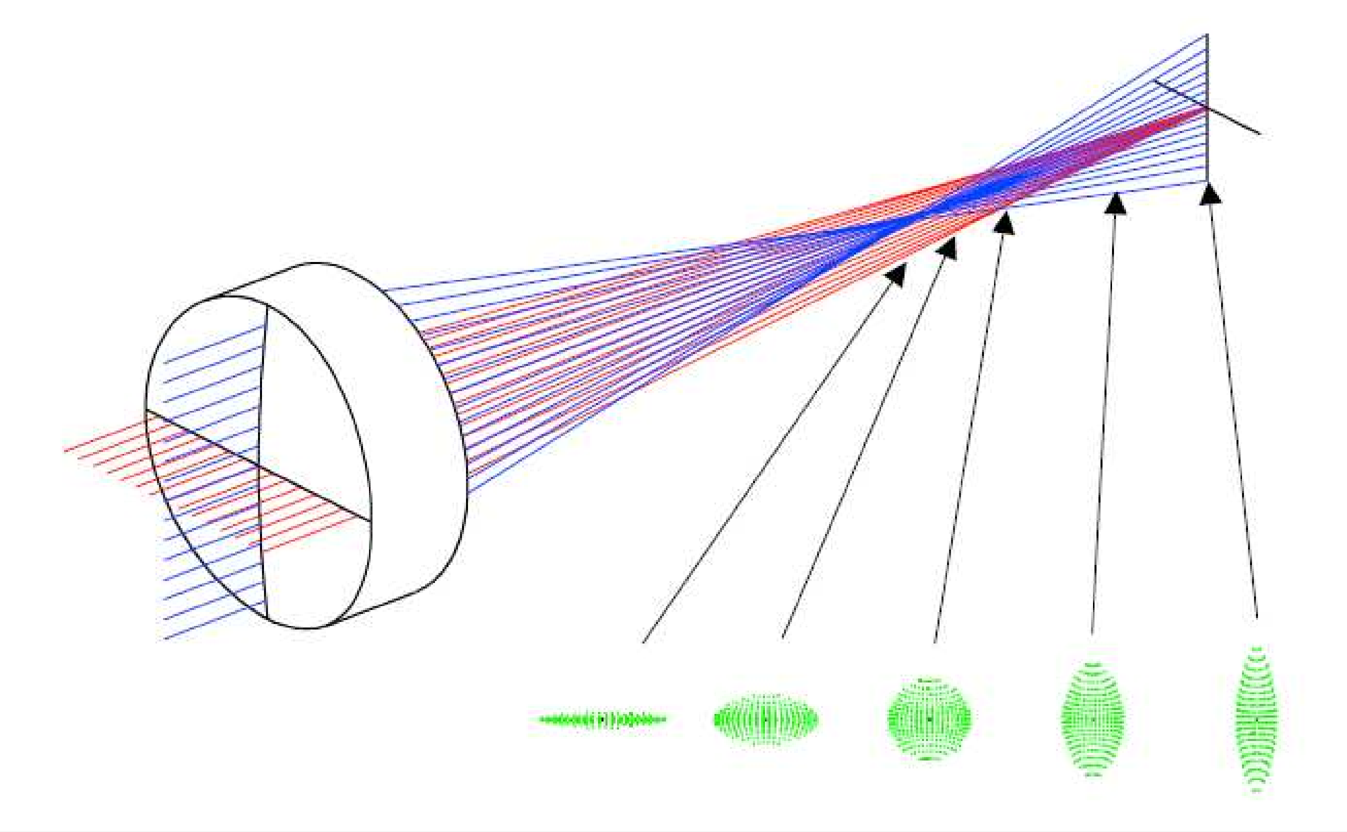
Oblique astigmatism due to a concave mirror¶



- **Characteristic pattern is an elongation along symmetry axis, or orthogonal to it.**
- **Furthermore, as one moves through focus, axis rotates by 90º**
- **In-focus images are symmetrical and round**

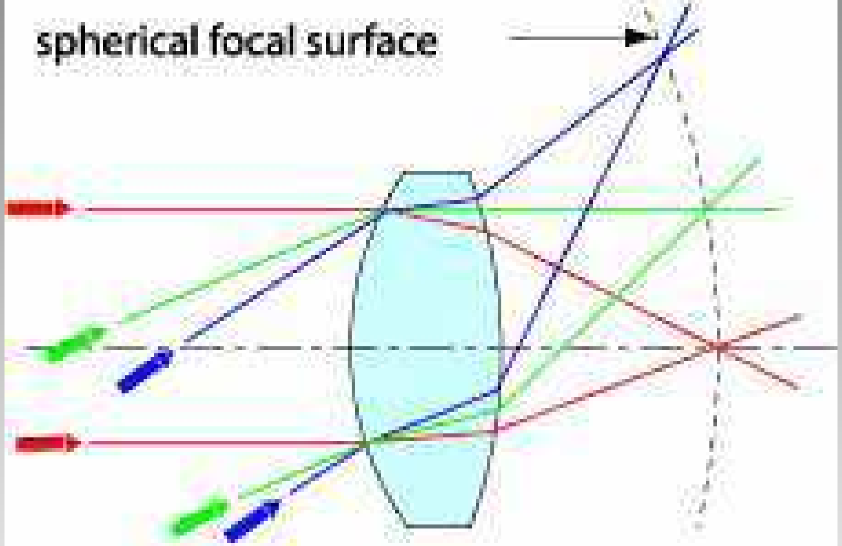
Optical Aberrations

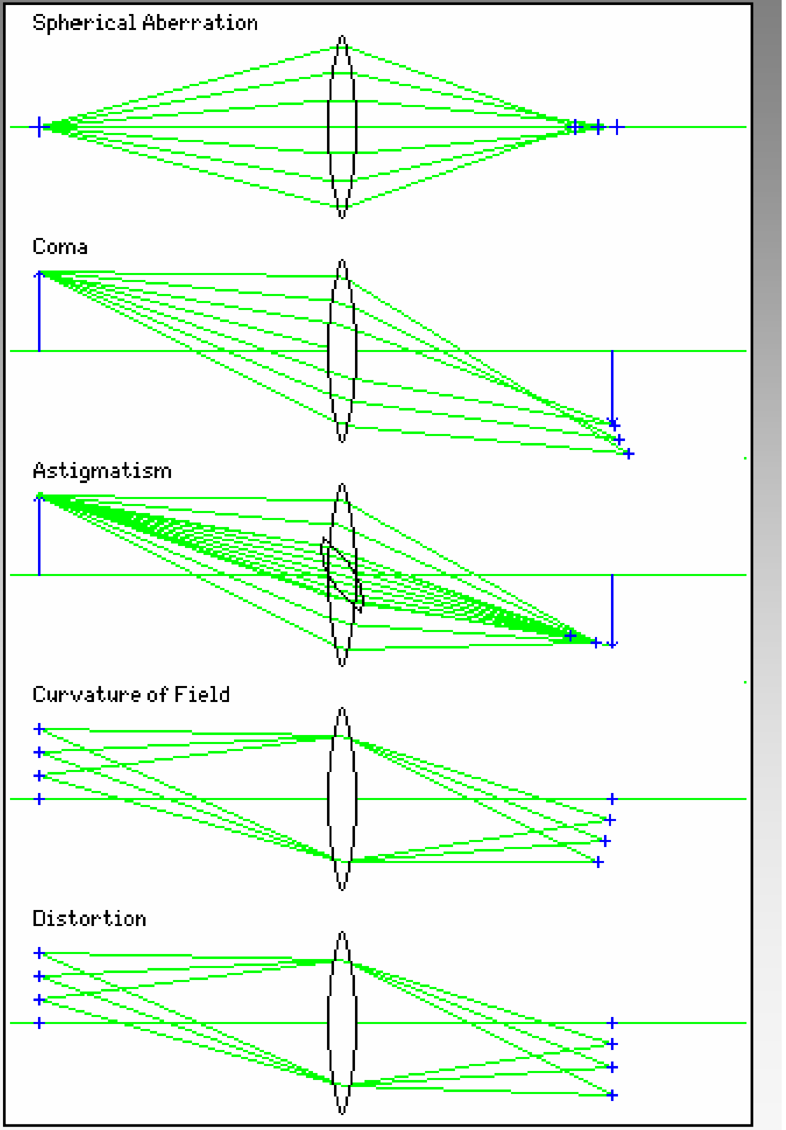
3. Astigmatism



Optical Aberrations

4. Field Curvature

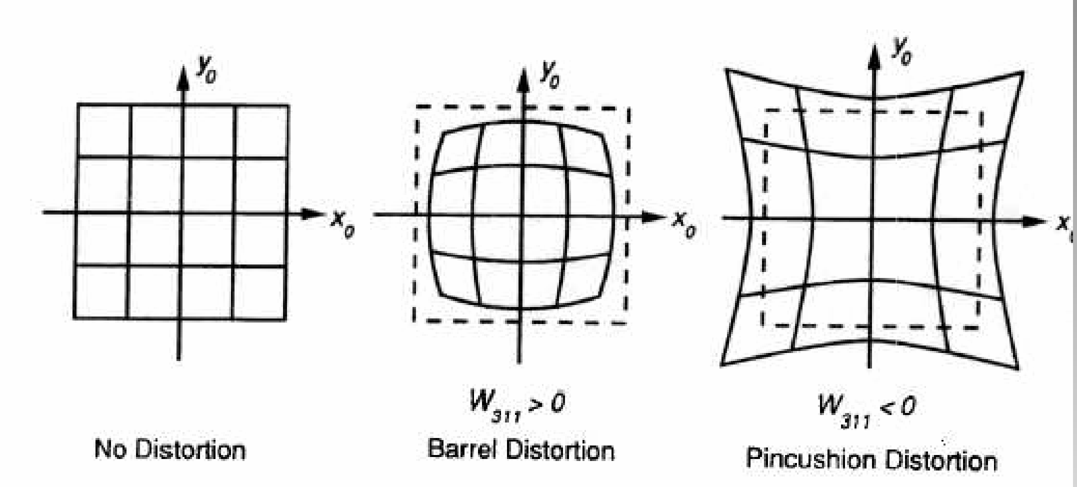




- Causes curvature of the focal plane.
- Not compatible with a flat detector (like CCD).
- In the past photographic plates could be slightly bent to accommodate
- Modern large & flat detectors require additional field-flattening optics

Optical Aberrations

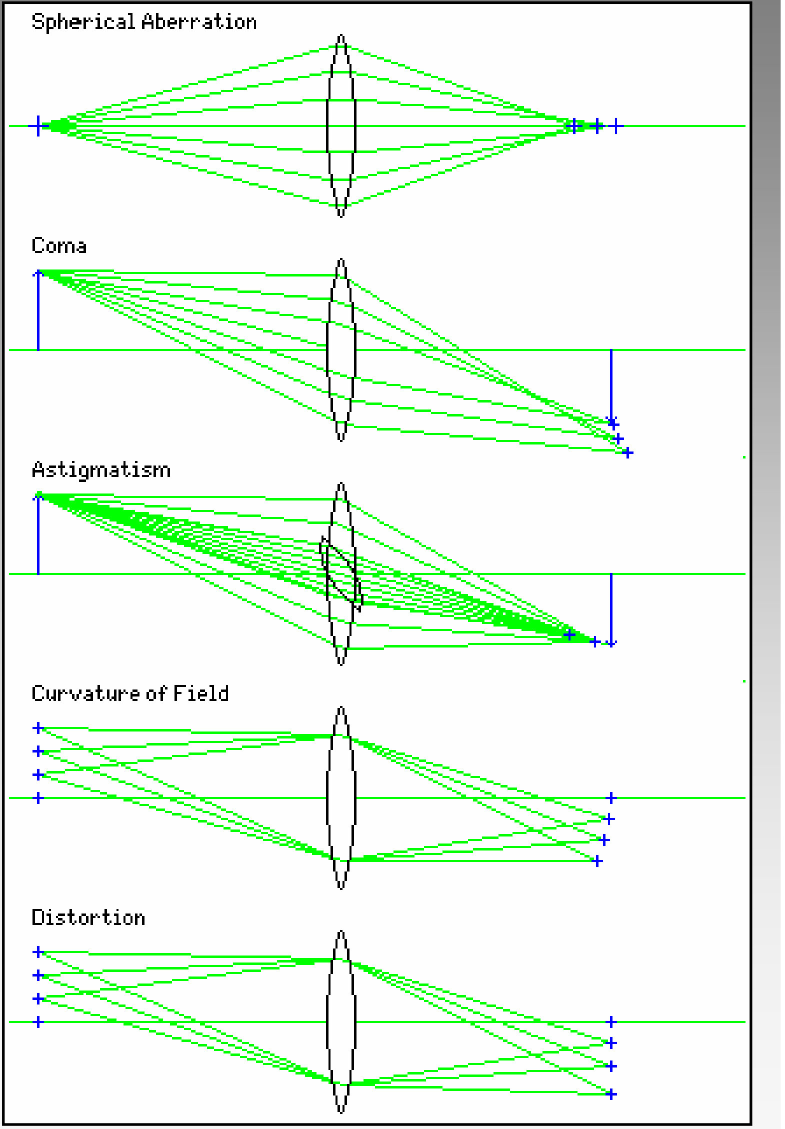
5. Field distortion



No Distortion

Barrel Distortion

Pincushion Distortion

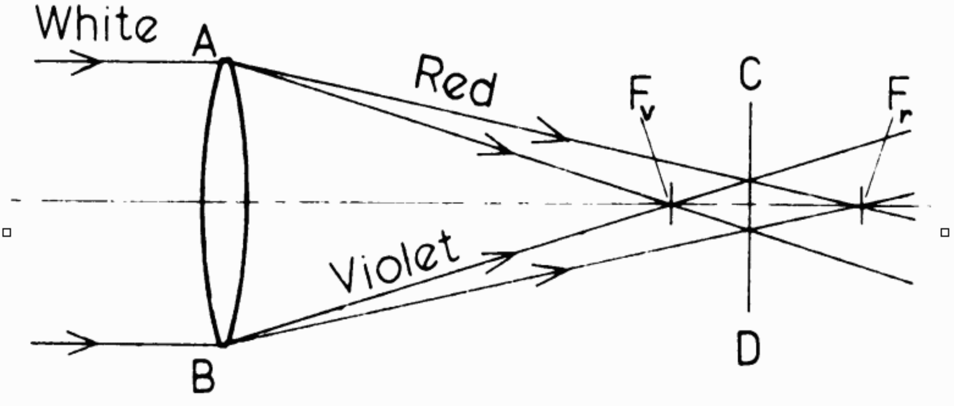


- Effectively a change of magnification across the FoV
- Can “stretch” (pin cushion) or “squeeze” (barrell) images.
- Need to map out distortion in order to do astrometry (accurate position measurement)

Optical Aberrations

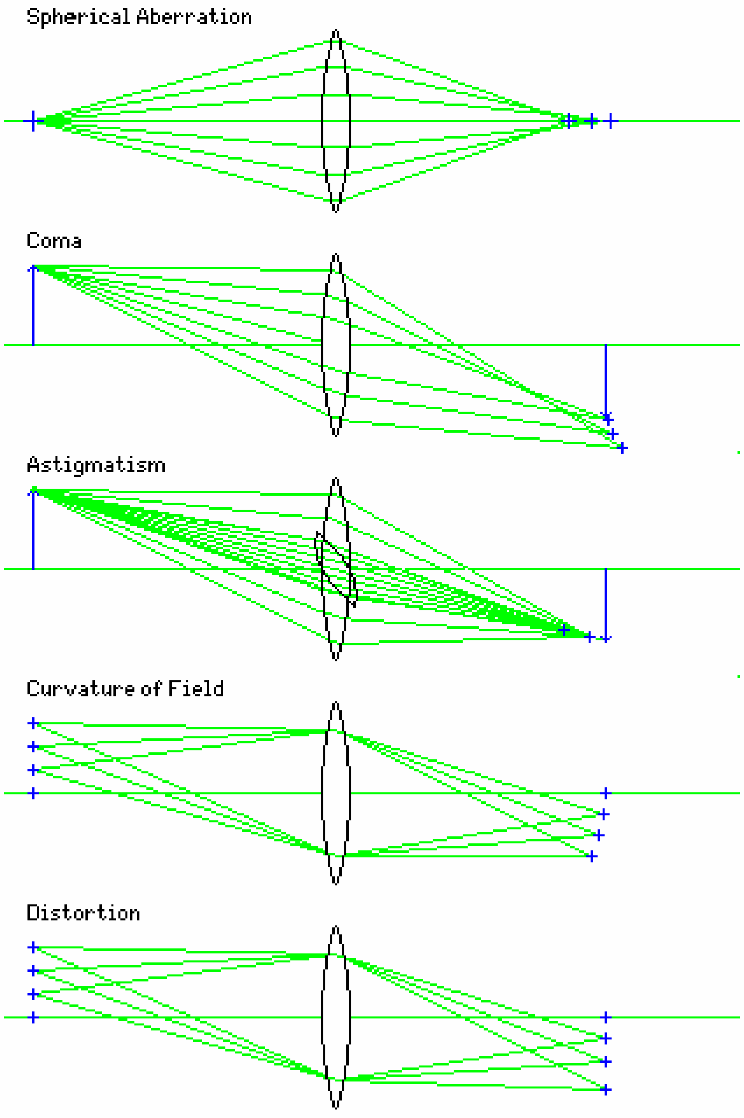
6. Chromatic effects

- For all lenses (not mirrors) need to add in the effects of refraction



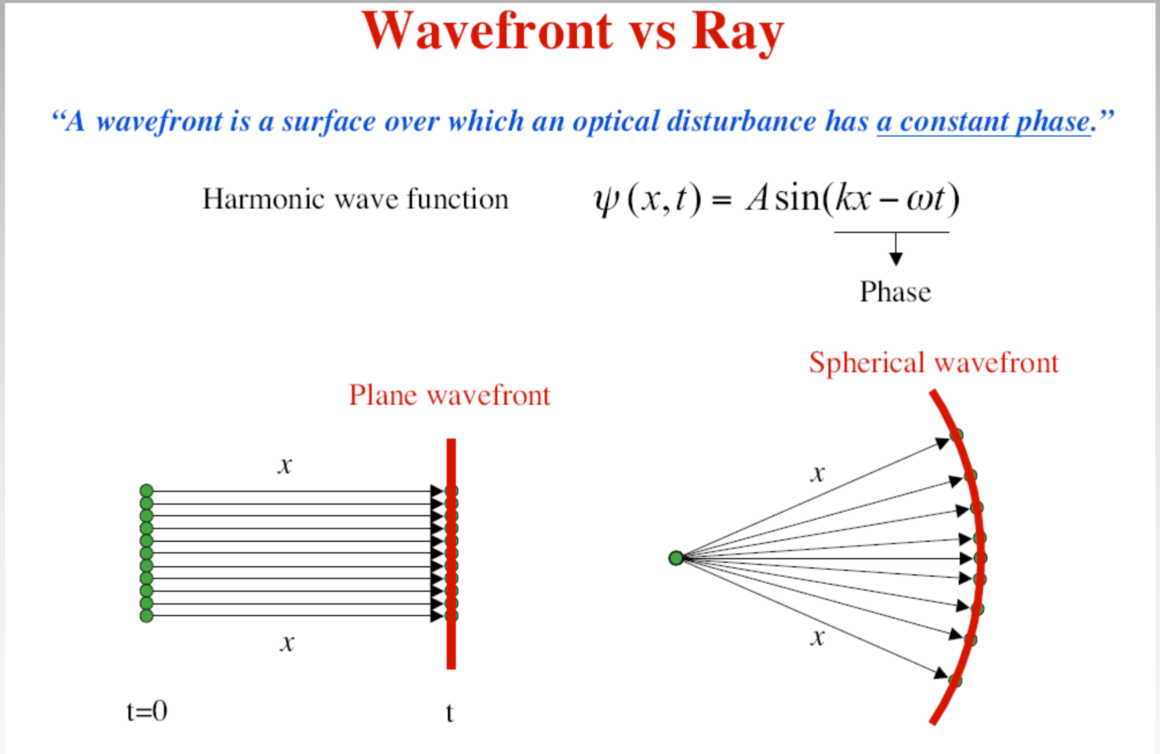
Chromatic·aberration·by·a·biconvex·lens¶

- These are called *chromatic aberrations*
- Can correct, to some extent, for the effects by using combinations of materials (glasses) with different refractive index and wavelength dependencies



Optical Aberrations: Zernike polynomials

- **Can describe optical aberrations as a wavefront perturbation**
- **Consider the *entrance pupil* (e.g. objective lens in a refractor) and the imperfections of this surface**
- **Can describe aberrations as phase changes that change with position over such a pupil**



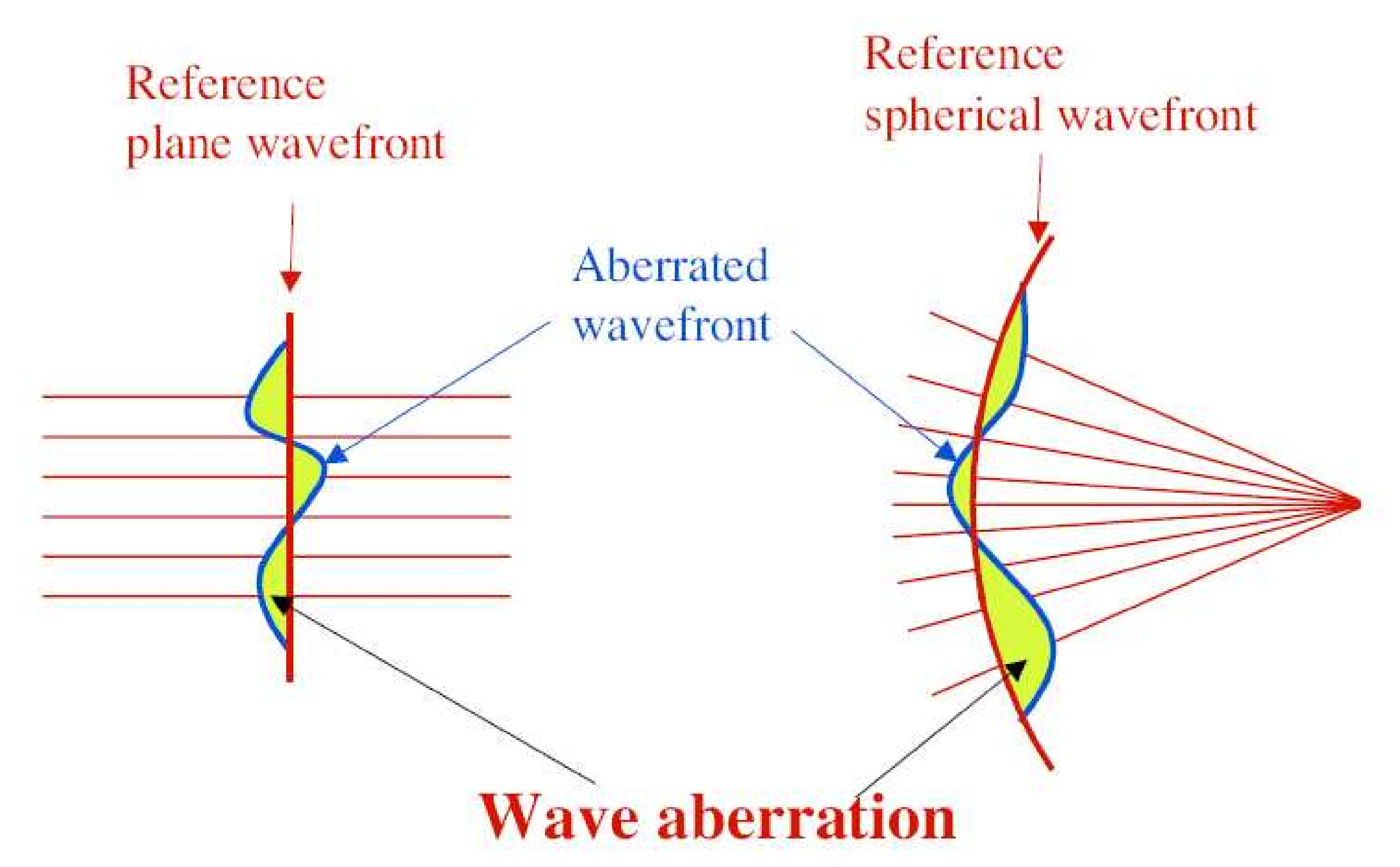
Wavefront vs Ray

"A wavefront is a surface over which an optical disturbance has a constant phase."

Harmonic wave function $\psi(x,t) = A\sin(\underbrace{kx - \omega t}_{\text{Phase}})$

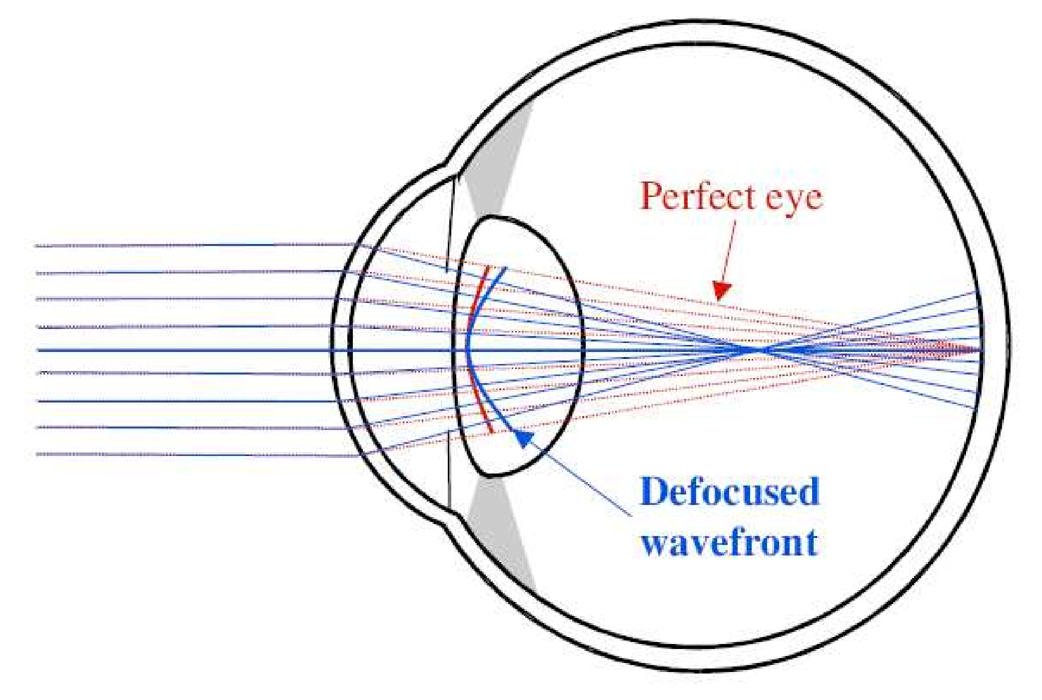
Optical Aberrations: Zernike polynomials

- **Wavefront perturbations**



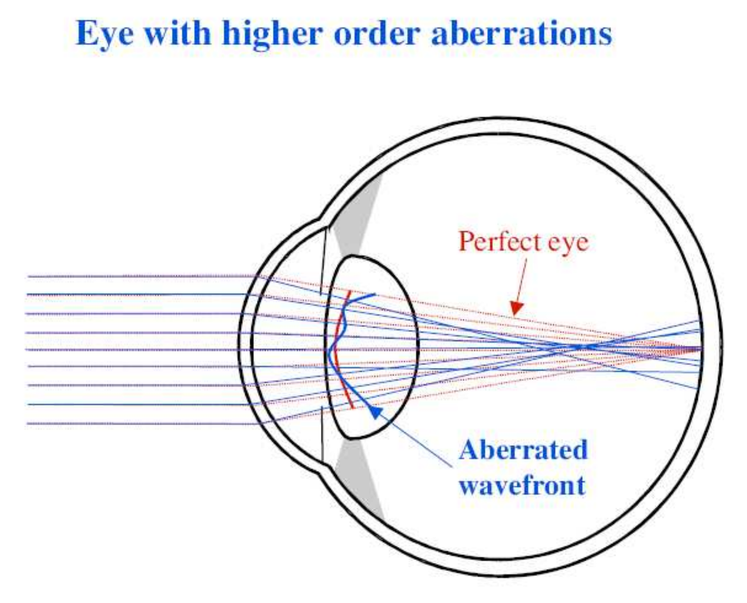
Optical Aberrations: Zernike polynomials

- **Example of an aberration (de-focus)**



What is this aberration commonly know as?

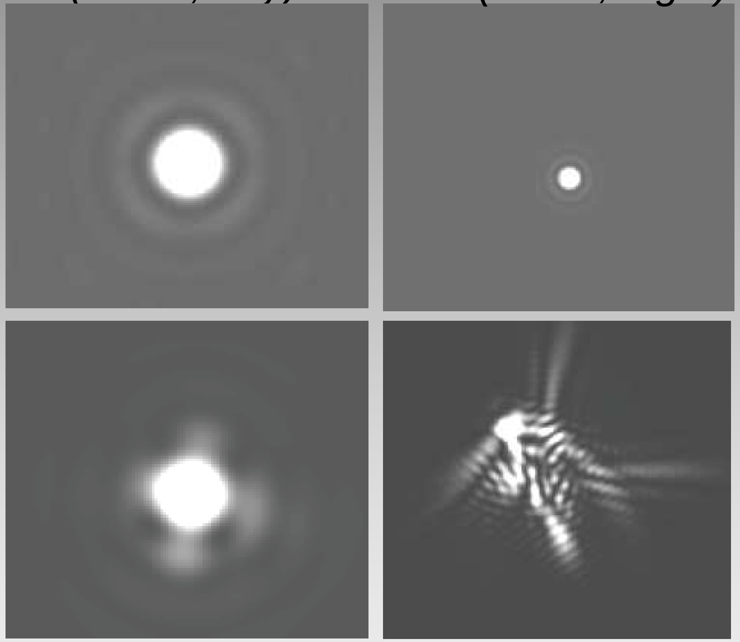
Aberrations in the Human Eye



PSFs for eye

Undilated pupil (2 mm; day)

Dilated (6 mm; night)

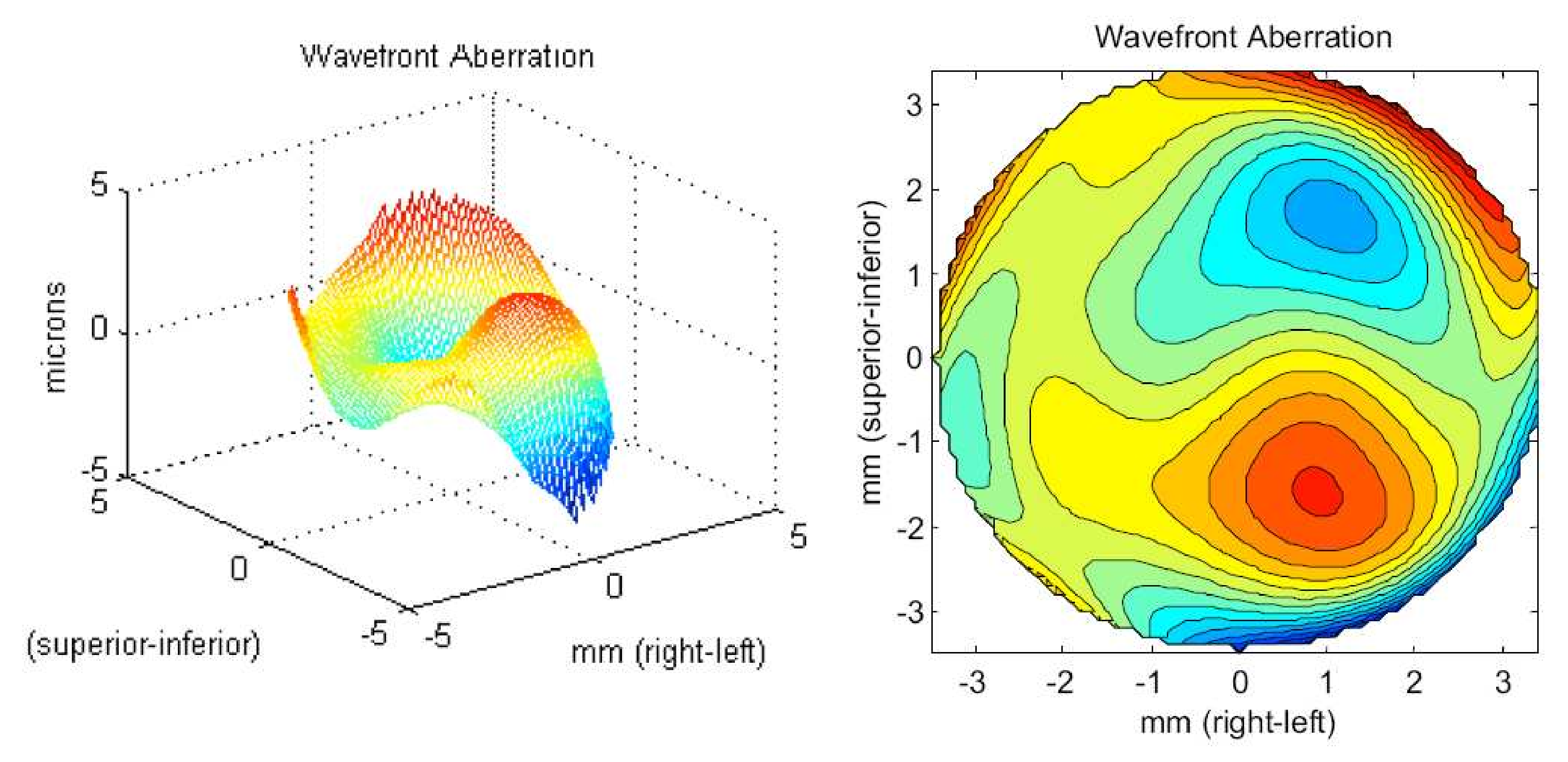


Ideal

Real

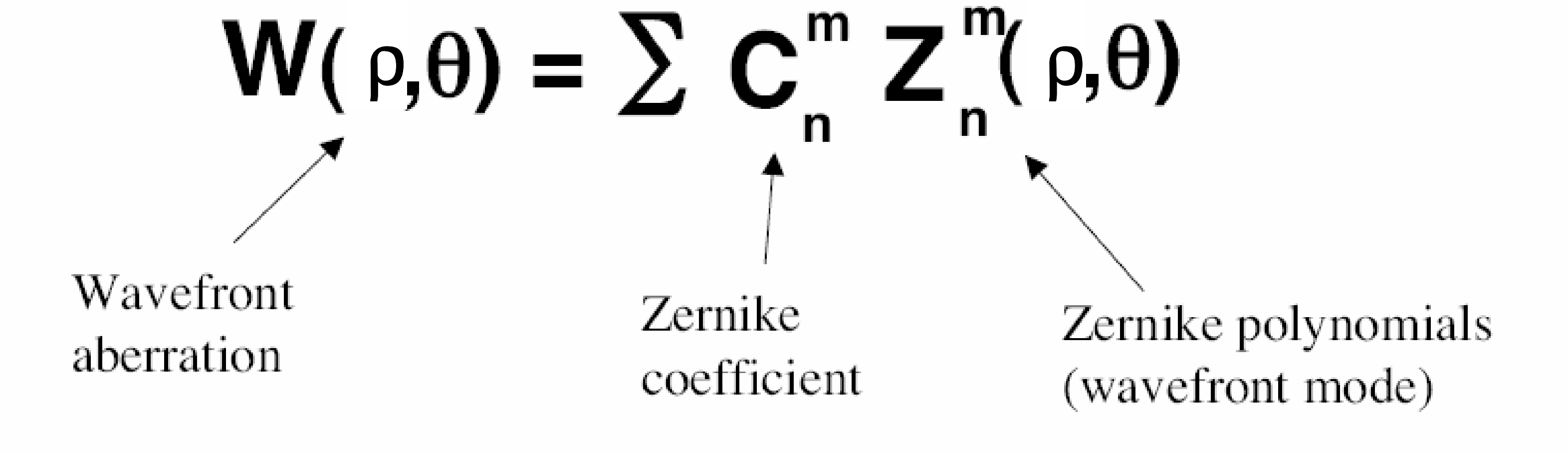
Optical Aberrations: Zernike polynomials

- **Can describe the phase variations as a *surface* showing departure from the ideal wavefront**



Optical Aberrations: Zernike polynomials

- **Mathematically, describe as a surface in ρ, θ coordinates**



$$W(\rho,\theta) = \sum C_n^m Z_n^m(\rho,\theta)$$

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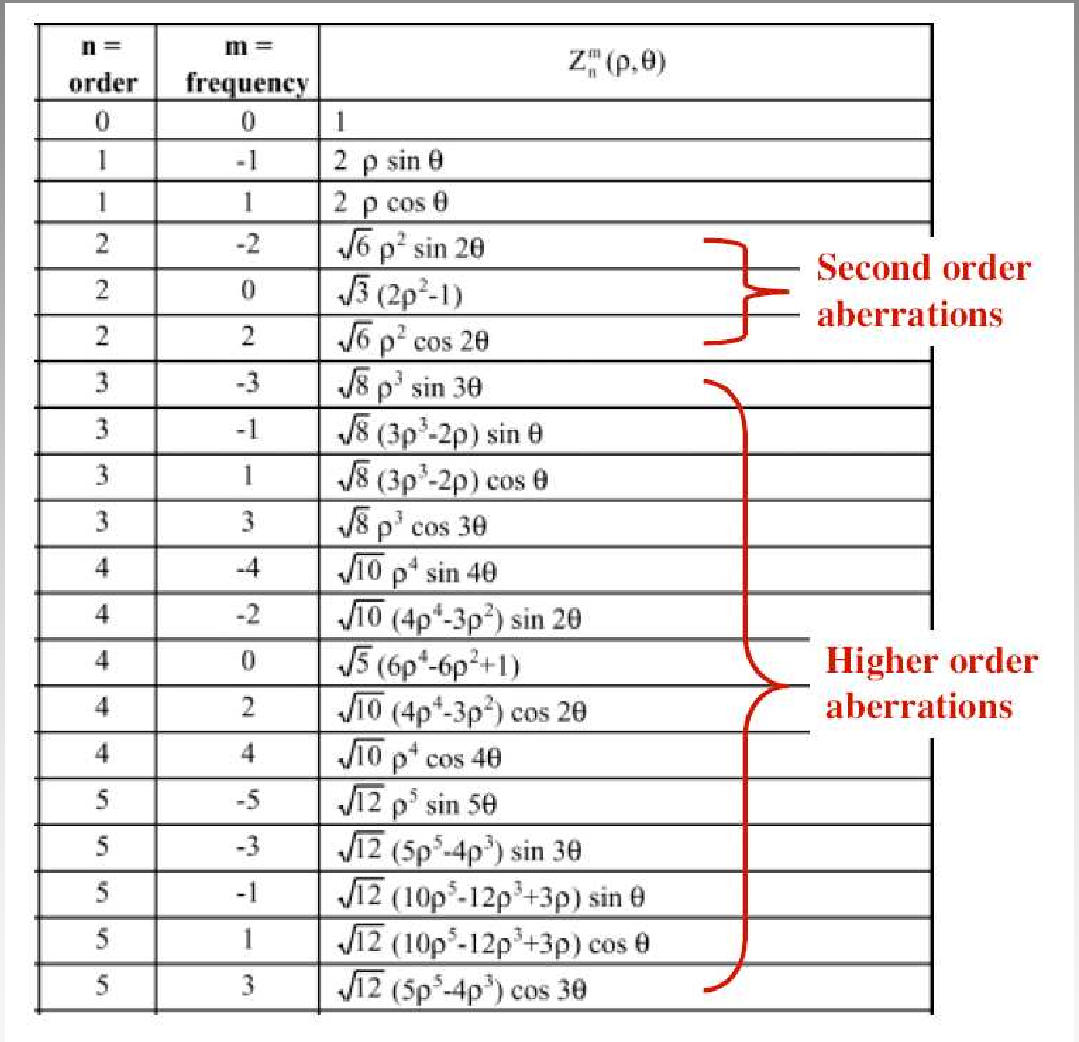
Optical Aberrations: Zernike polynomials

- **Zernike polynomials:**



n = order	m = frequency	$Z_n^m(\rho,\theta)$
0	0	1
1	-1	$2\ \rho \sin\theta$
1	1	$2\ \rho \cos\theta$
2	-2	$\sqrt{6}\ \rho^2 \sin 2\theta$
2	0	$\sqrt{3}\ (2\rho^2-1)$
2	2	$\sqrt{6}\ \rho^2 \cos 2\theta$
3	-3	$\sqrt{8}\ \rho^3 \sin 3\theta$
3	-1	$\sqrt{8}\ (3\rho^3-2\rho) \sin\theta$
3	1	$\sqrt{8}\ (3\rho^3-2\rho) \cos\theta$
3	3	$\sqrt{8}\ \rho^3 \cos 3\theta$
4	-4	$\sqrt{10}\ \rho^4 \sin 4\theta$
4	-2	$\sqrt{10}\ (4\rho^4-3\rho^2) \sin 2\theta$
4	0	$\sqrt{5}\ (6\rho^4-6\rho^2+1)$
4	2	$\sqrt{10}\ (4\rho^4-3\rho^2) \cos 2\theta$
4	4	$\sqrt{10}\ \rho^4 \cos 4\theta$
5	-5	$\sqrt{12}\ \rho^5 \sin 5\theta$
5	-3	$\sqrt{12}\ (5\rho^5-4\rho^3) \sin 3\theta$
5	-1	$\sqrt{12}\ (10\rho^5-12\rho^3+3\rho) \sin\theta$
5	1	$\sqrt{12}\ (10\rho^5-12\rho^3+3\rho) \cos\theta$
5	3	$\sqrt{12}\ (5\rho^5-4\rho^3) \cos 3\theta$

Second order aberrations

Higher order aberrations

Optical/IR Observational Astronomy

Telescopes I: Optical Principles

Optical Aberrations: Zernike polynomials