6 Designing and building astronomical instruments

Developing new instrument: many important factor & constraint

6.1 Basic Requirements

First step: Understanding/Defining the applications (science goal)
Vital to design instrument

- **Design (Slit spec, fiber spec, multi slit, …)**
- **Constraint(FoV, angular resolutions, wavelength range, …)**

↑ **Depend on Science goal**

Too many science goals: **very complex instrument**

Define science goal⇒choose approaches/designs

6.2 Overall System Layout

Designing process⇒

Laying out essential components & interconnections

Preferable approach: **Partition into modules**

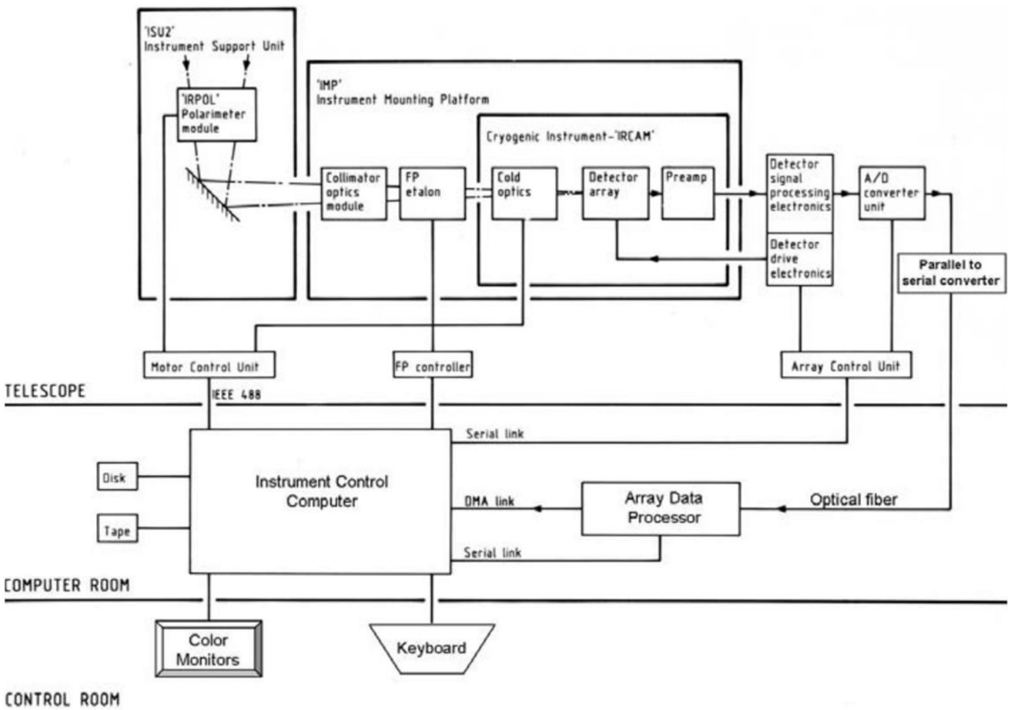


Figure 6.1. A block diagram layout of an entire camera system for a large telescope. The illustration is for IRCAM, the first infrared camera system developed for the 3.8 m U.K. Infrared Telescope.

Example of design of IR Camera

Basic features is similar to modern instrument

Fundamental items for instruments:

1. Detector
2. Opto-mechanical system
3. Enclosure and cooling system
4. Signal-processing hardware/ADC
5. Electronics for detector
6. Timing logic and synchronization circuits
7. “motion control/maintain” system
8. Electronic interface to a computer
9. Host computer
10. Image display system & image processing software

6.3 Optical Design

Young astronomers & Anyone interested in:
Important to train optical design

6.3.1 First order to ray tracing

Process of optical design:

1. **Basic design**
2. **Constraints**
3. **Performance specification**
4. **Ray tracing & optimization**
5. **Tolerance analysis**

Basic design

Design with considering of simple condition

(Simple lens, Plate Scale, FoV, F number, ･･･)

⇒**Construct basic design**

- **Simple lens (without considering of aberrations): Estimate required power, beam size, and detector size**
- **Simple displacement & deviations of plate Consider the displacement of filter, window of vacuum enclosures, polarizing beam-splitters**

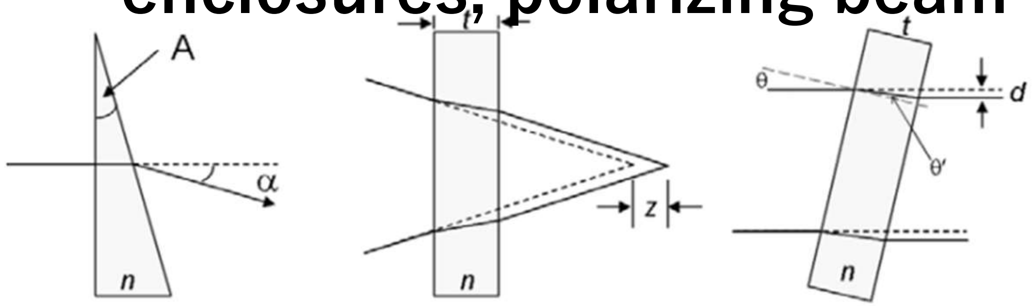


Figure 6.3. The effect of wedges and tilted plane-parallel plates on the optical beam.

$$\left.\begin{aligned} &\alpha \approx (n-1)A && \text{thin wedge} \\ &z = \frac{(n-1)t}{n} && \text{parallel plate in converging beam} \\ &d = t \sin\theta \left(1 - \frac{\cos\theta}{n\cos\theta'}\right) && \text{displacement by parallel plate} \end{aligned}\right\} \quad (6.1)$$

Identify & list all the known constraints

- Wavelength range
- Transmittance
- Desired back focal length
- Size
- Weight
- Ability to test and align optics
- Cost of fabrication

…

Ray tracing

Performed to check & correct optical design

Program for ray tracing (like Code V released by ORA):

- Analyze the system entered to computer
- Optimize a given design or search for different designs within arbitrary constraints

Useful to study what the effect of variations in design, and
What compensation techniques can be applied

6.3.2 Aberrations

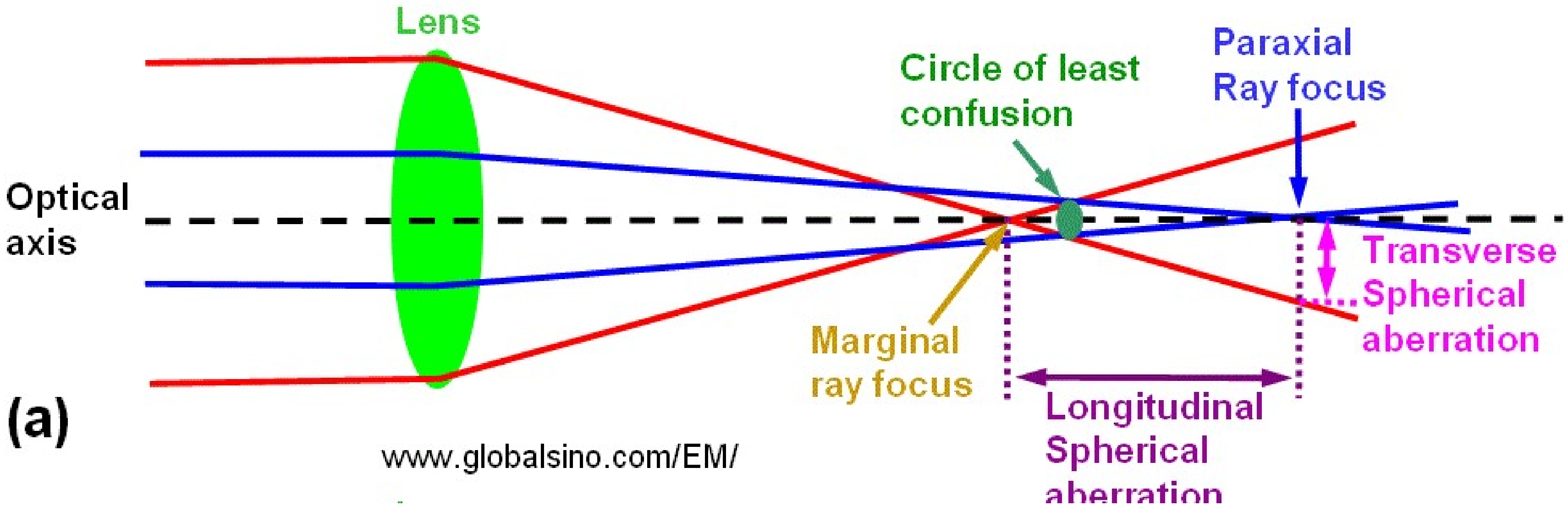
Aberrations: geometric factors reduce image quality

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \frac{\theta^9}{9!} - \cdots \quad (6.2)$$

① $\sin\theta \approx \theta$: possible to obey the paraxial equation/theory (irrespective of value of θ in Snell's Law)
② $\sin\theta \approx \theta - \theta^3/6$: we are led to a useful set of Seidel aberrations

Seidel aberrations: general term for aberrations in monochromatic light
Aberrations of multi-color: Seidel + chromatic aberrations

Spherical aberration



Diameter of blur circle

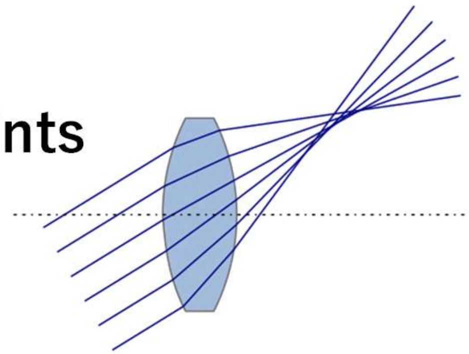
$$\left.\begin{aligned} \text{spherical mirror:} \quad & \beta = 1/128F^3 \\ \text{parabolic mirror:} \quad & \beta = 0 \\ \text{simple lens:} \quad & \beta = n(4n-1)/128(n+2)(n-1)^2F^3 \end{aligned}\right\} \quad (6.3)$$

Coping method

- Small aperture (pupil)
- Neutralize with positive and negative element
- Eliminate with parabolic surface

Coma aberration

Caused by parallel rays from off-axis points



Angular size of tangential coma:

spherical mirror: $$\beta = (3/16)(\theta/F^2)[1 - z/2f] \tag{6.6}$$

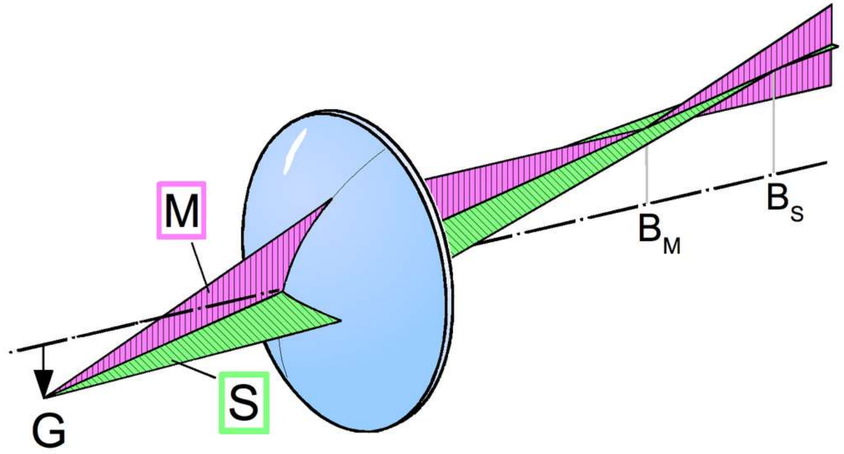
Coping method

- Small aperture
- Diaphragm at the center of spherical mirror (Schmidt Telescope)
- Fulfill Abbe condition

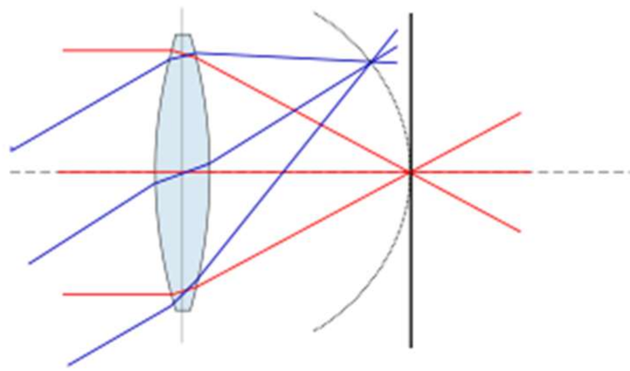
$$\sin\theta/\sin\theta' = \theta_p/\theta'_p = \text{constant} \tag{6.7}$$

Astigmatism

- Rays that propagate in two perpendicular planes have different focus
- Caused by tilted plates (dichroic beam-splitter, filter placed in a converging beam)
- Blurred image is seen between two focuses



Field curvature



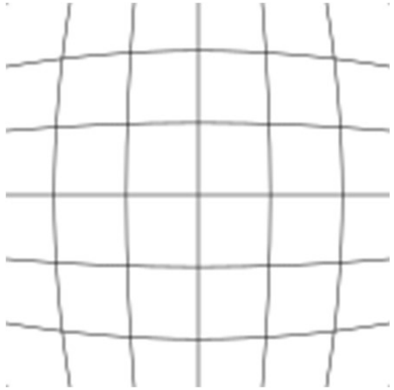
- Natural tendency for optical systems to image better on curved surfaces (Petzval surface) than on flat planes
- Positive element and negative one shows opposite curvature

Coping method

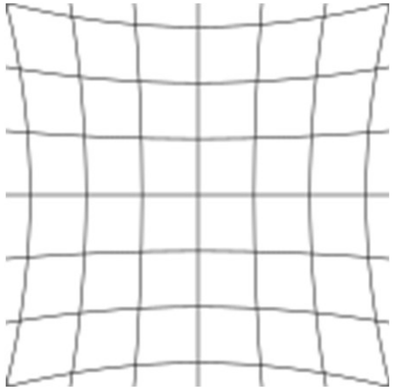
- Field flattening lens
- Correct with combination of two elements

Distortion

- Image of an off-axis point does not form at ate predicted position (paraxial theory)
- 3 types:
  1. Pincushion
  2. Barrel
  3. Keystone



Barrel

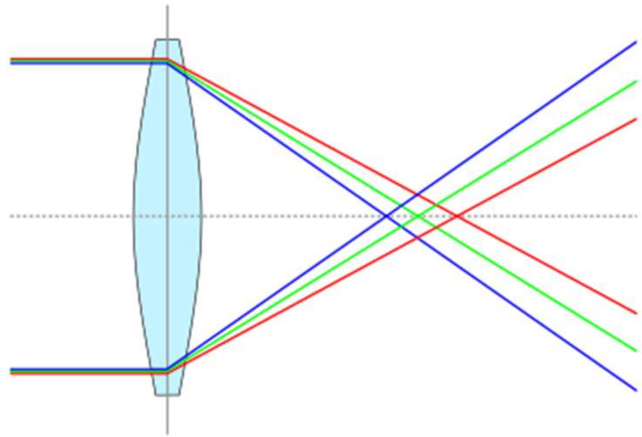


pincushion

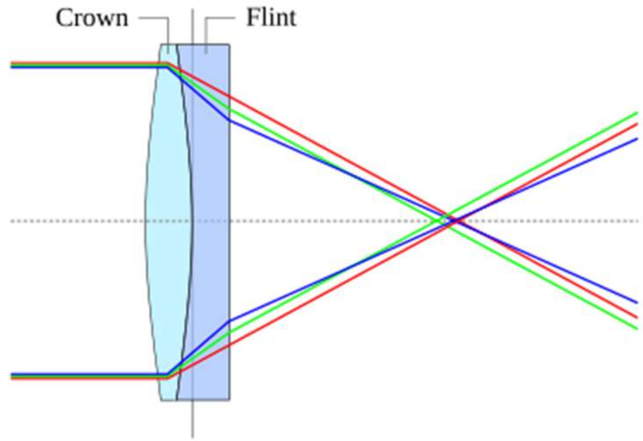
Coping method:
Remove with computer processing

Chromatic aberration

- Caused by the difference of refractive index depends on wavelength
- Longitudinal chromatic aberration: difference in focus
- Lateral chromatic aberration: difference in image height
- No chromatic aberration with mirror



Example of longitudinal chromatic aberration



Coping method:
Correct with combination of two lenses (different material)

6.3.3 Wavefront Error

Optical path difference (OPD): difference between the real wavefront and the best fitting spherical surface
Wavefront Error: Deviation of the observed wavefront from perfect (specified in terms of the peak-to valley OPD)

Wavefront Error: deteriorate PSF
⇒**Decrease image quality and intensity at the center**

Strehl ratio: fraction of light within any angular radius θ

$$S = \exp[-(4\pi\sigma/\lambda)^2]$$

(σ : rms amplitude of the surface roughness)

Quantified performance of the optical design

- Performed with distortion map, limits of scattering, wavefront error budget, etc.
- Ray-tracing programs provide several important tools

1. Spot diagrams(cluster of impact points on the focal plane)
2. Encircled energy (total amount of energy within a circle)
3. Tangential ray fans (variations of an aberration)
4. Modulation transfer function (modulations of image to estimate required resolution)

Control of aberrations/Making aspheric plates

Control of aberrations: making surface of the primary optical component to correct aberrations

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+K)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \cdots \quad (6.8)$$

Conic curve surface

Aspheric surface

$$\sum_{i=0}^{N} A_i Z_i(\rho, \varphi) \quad (6.9)$$

※ For deformable mirror and multiple mirrors

Aspheric plates: carved out with computer-controlled diamond-tipped cutters

Material of mirror support & attachments: same with mirror

⇒No requirement to consider differential thermal contraction

OAP(Off-Axis Parabola): section of a paraboloid that does not contain the vertex

- Correct coma aberration (Mersenne relay, use opposing off-axis parabolas)
- TMR(three-mirror relay): Use two OAP mirrors (big primary mirror and small secondary mirror) to lead light back to the other sections of primary mirror
- TMA (three mirror anastigmat): all three mirrors are conic (strong keystone distortion)

Spherical aberrations and achromatic doublets

Split the power and double the number of components (like Cooke triplet)

6.3.4 Coatings and interference filters

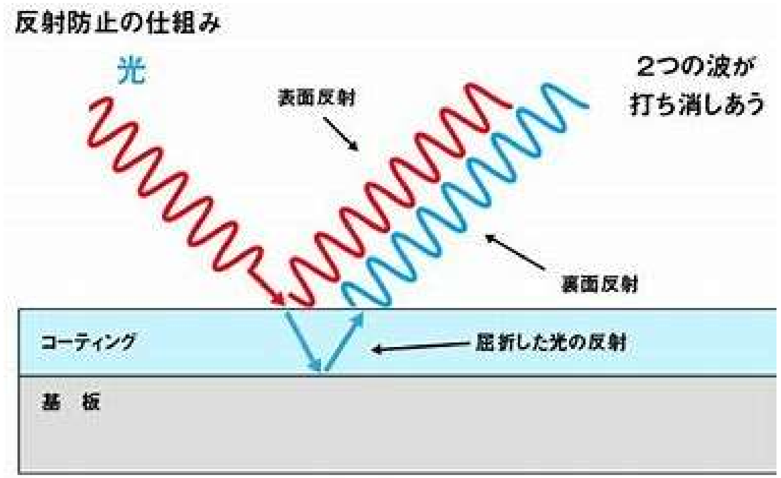
Anti-reflection coating: prevent reflection on optical components with coating on components

- Reflectance of a surface:

$$R = \left(\frac{n-1}{n+1}\right)^2 \tag{6.10}$$

- Basic relationship of interference:

$$2nd = (m + \tfrac{1}{2})\lambda \tag{6.11}$$



⇒Minimum thickness for coating: d= λ /4n(quarter-wave layer)
Ideal value of n: $\sqrt{n_g}$(n_g: refraction index of components)

Multi-layer coatings

- Using several materials to provide a reduction in reflectance in broad band wavelength
- Coatings on CCD: make quantum efficiency better (Silicon: $n=4 \Rightarrow 36\%$ reflection loss)

Narrow-band filter and Fabry Perot etalon

- Interference equation: $m\lambda = 2nd\cos\theta$
- Adjusting inclination (θ) $\Rightarrow$ change wavelength range