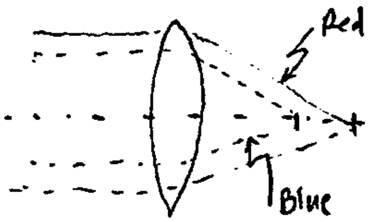
Telescopes and Telescope Optics

- Large optical/IR telescopes have not changed substantially in basic design in the last ~75-100 years

Refracting telescopes → Reflecting telescopes

Why?

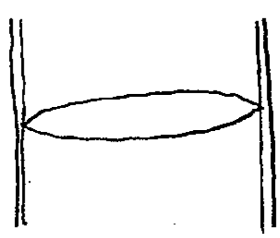
① Chromatic aberration



Refracting materials generally have indices of refraction that depend (sometimes very substantially) on wavelength ⟹ different foci

Can correct over limited ranges of wavelength (as we will see in designs of spectrograph cameras) but can be complex and difficult.

② Difficulty in supporting large optics by edge



Different gravity vectors cause sagging, deformation of lenses

These difficulties, plus the ability to sputter durable Al coatings on glass, led naturally to reflectors as the design of choice for large aperture telescopes.

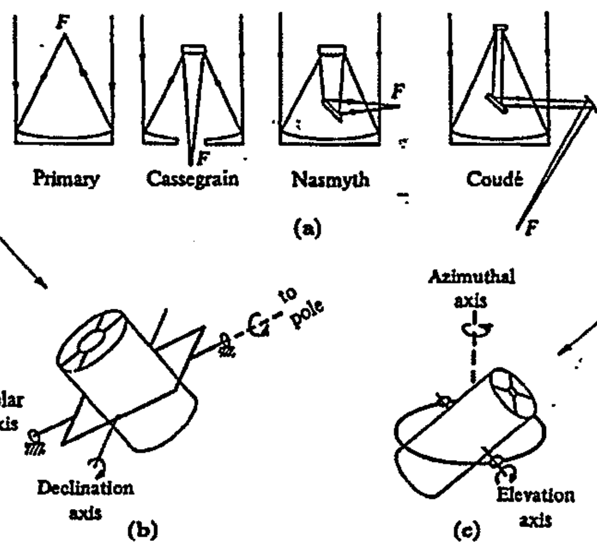


Fig. 4.1. (a) Different focal configurations. Pointing of (b) equatorial and (c) altazimuth ground-based telescopes

Telescope configurations

- "Equatorial Mount" ; Axes of Motion are RA, DEC ; e.g., Palomar 200" telescope — tracking achieved by moving in Right Ascension only

Most telescopes were of this design until ~ 1980's

- Altitude-Azimuth

Basically, telescope sits on a flat turntable (azimuth) and can move in elevation relative to zenith / horizon.

Complications:
- Must move in both axes simultaneously, at varying rates, to track objects on the sky

  ⟹ need computer, rather than mechanical, control

- The field seen by the telescope rotates with respect to the telescope frame

  ⟹ must have a rotator for science instrument

Telescope Foci

Telescope primary mirrors are characterized by their diameter (D) and focal ratio (f), defined as

$$f = \frac{EFL}{D}$$

e.g., P200 f/3.3 at prime focus (~~f/9~~ f/16 for Cass)
Keck f/1.75 (f/15 for Cass, Nasmyth)

The EFL of the focus $\left\{\begin{array}{l}\text{prime}\\ \text{nasmyth}\\ \text{cassegrain}\\ \text{coudé}\end{array}\right\}$ controls the image scale (usually ″/mm) at the focal plane.

e.g., P200 f/3.3 ⟹ EFL = 3.3 (200) 25.4 = 16,764 mm

$1'' = 4.85 \times 10^{-6}$ radians $= \Delta\theta$

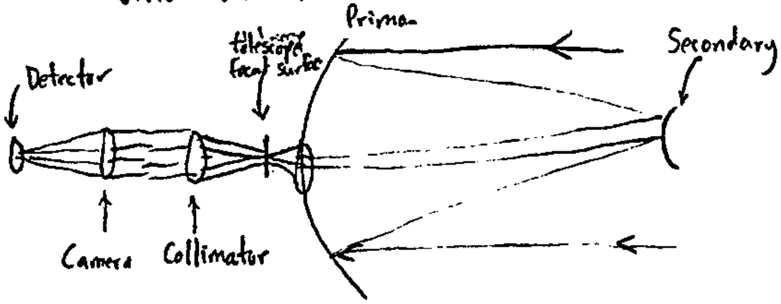
⟹ focal scale at prime focus is $EFL \cdot [\Delta\theta] \Rightarrow 0.081$ mm/arcsec
(for 1″ on sky)

⟹ "plate scale" is $\frac{1}{0.081} = 12''\!.3$/mm (or $0''\!.295$/24 microns).
⟹ perfect sampling for ~1″ seeing

for Keck, no prime focus focal station

f/15 Cass ⟹ EFL = 150,000 mm ⟹ 0.73 mm/arcsec
⟹ 1.37″/mm ⟹ $0''\!.03$/24 microns

⟹ focal or plate scale at Keck is ridiculously small for seeing-limited images ⟹ instruments must "re-image" onto detectors.



Re-imaging is done by a camera (more on this later).

Telescope Design Issues

(1) Primary mirror collecting area

- obviously, the larger the better. However, gap from 1949–1992 in going beyond 5m primary. Why?

Difficulty in producing a large mirror that can be adequately supported under gravity (not to mention manufacturing difficulty.) Also thermal properties become difficult to manage.*

Solutions:
- Segmented primary [e.g. Keck] each segment is ~1.8m in diameter, active control system keeps segments to proper figure under gravity
- Thin meniscus - thin cast mirror is deliberately flexible, controlled via actuators on back side of primary (e.g. VLT 8m)
- Borosilicate Honeycomb (Steward Mirror Lab- Magellan, MMT 6.5m) Rigid mirror, relatively thick – extremely important to control temperature

Thermal considerations:

Consider thermal properties of various glasses

$$\frac{\Delta l}{l} = \alpha \Delta T$$

α ← coefficient of thermal expansion

pyrex (P200") $\alpha = 3\times10^{-6}\ K^{-1}$

zerodur (Keck, VLT) $\alpha = 1\times10^{-7}\ K^{-1}$ (very expensive)

Want wavefront errors $\frac{\Delta\lambda}{\lambda} < \frac{\lambda}{4}$; @ 500 nm (5000 Å),

e.g., $\Delta T_{crit} \simeq 0.05\ ^\circ K \left(\frac{50\,cm}{l}\right)\left(\frac{3\times10^{-6}}{\alpha}\right)$ temperature differences over mirror could have deleterious effect on images!

Suppose ambient temperature changes. How fast can the mirror equilibrate?

$$Q = \text{heat flux} = \underbrace{K}_{\sim 1\ \mathrm{W/m/K}} \nabla T$$

h = thickness of glass

$$\Delta E \simeq \left(\tfrac{3}{2} k \Delta T\right) \underbrace{N}_{\frac{h\rho}{4 m_A}} \quad ; \quad Q \Delta t \simeq E = K \Delta T$$

$$\Rightarrow \Delta t = \frac{3}{2} \frac{k}{2} \frac{h^2 \rho}{4 m_A} \frac{1}{K} \Rightarrow \boxed{\Delta t\,(\Delta T = 1) \approx 2\,\text{hours} \left(\frac{h}{10\,\mathrm{cm}}\right)^2}$$

② Field of View

Generally speaking, the "faster" the primary (i.e., the smaller the f-number) the easier it is to achieve larg FoV's.

Several issues: vignetting (how large is the secondary for a Cass system;

image quality - how far off-axis are acceptable images formed? Can one access

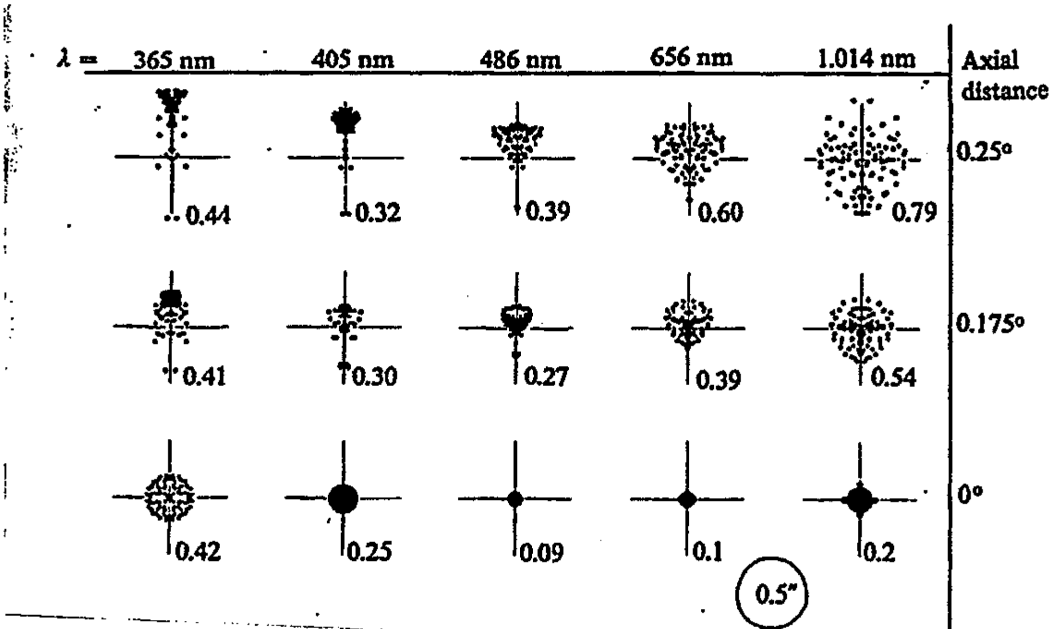
control of focal surface - many wide-field telescopes produce good images but have a very curved focal surface.

There is usually a compromise required between quality of the images and size of the field of view.

③ Delivered Image Quality

It has been realized in the last ~15 years that with careful control over thermal effects in domes, the best astronomical sites can deliver images w/ FWHM ~ 0.″3 even in the visible, thus the goal to not be limited by telescope optics has become more difficult to achieve [More on this in a minute]

There are many contributions to image quality, from inherent aberrations due to the shape of the mirror, to distortions in the wavefront introduced by imperfect polishing of surface.



Full optical systems are normally modeled by computer, producing a "ray trace". Usual figure-of-merit is the angular diameter of a circle enclosing 80% of the light from a point source. A very good figure is $\theta_{80} \approx 0.''3$ (the original spec for the Keck telescopes). Compromises are almost always required.

④ <u>Where are the foci</u> ?

This is relevant for both optical and mechanical considerations.

<u>Prime Focus</u>: Usually widest field, best "plate scale", but focal surface can be badly curved, there may be weight limitations, PF cage obscuration of primary

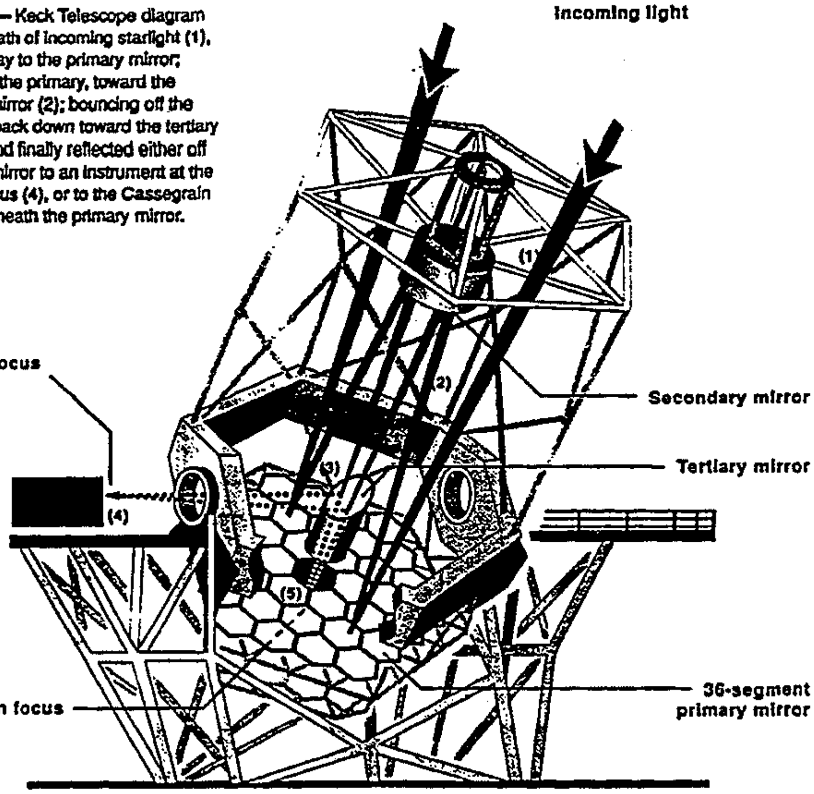
<u>Cassegrain</u> : Allows use of larger instruments, often good for spectrographs, ability to use a secondary fine-tuned to provide desired properties of scale + focal surface (+ reduce aberrations)

(4) (Continued)

Coudé : Traditionally this is where huge high-resolution spectrographs were placed, very long EFL, too slow on 8-10m telescopes.

Nasmyth : This is the focus of choice for large instruments on large telescopes - instruments are stationary, same secondary as for Cass w/ tertiary mirror

Light Path — Keck Telescope diagram shows the path of incoming starlight (1), first on its way to the primary mirror; reflected off the primary, toward the secondary mirror (2); bouncing off the secondary, back down toward the tertiary mirror (3); and finally reflected either off the tertiary mirror to an instrument at the Nasmyth focus (4), or to the Cassegrain focus (5) beneath the primary mirror.



Credit: California Association for Research in Astronomy

e.g. Keck telescope has:

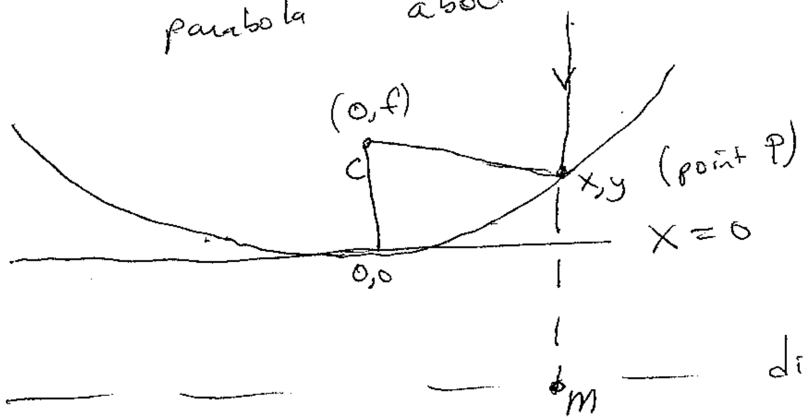
f/15 Cassegrain [LRIS, ESI]
f/25 forward Cassegrain [IR module]
f/40 "bent" Cassegrain ["Visitor port"]
f/15 Nasmyth [HIRES, AO, DEIMOS, NIRSPEC]
(2 per telescope)

For fixed diameter focal ratio determines the curvature of the optics
Smaller f, more curved optic, harder to manufacture + polish

Telescope Design

Want surface: for a set of rays || to the optical axis, all are reflected by the surface to a single point, the focus.

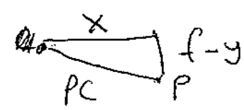
This is a paraboloid, surface formed by rotating a parabola about its axis.



directrix $x = -f$
NB ~ the directrix represents the wavefront if there were no parabola.

Definition of a parabola

$PC = PM$



$PC = \left[x^2 + (f-y)^2\right]^{1/2}$

$PM = y + f$

$PC = PM \qquad x^2 + y^2 + f^2 - 2fy = y^2 + f^2 + 2fy$

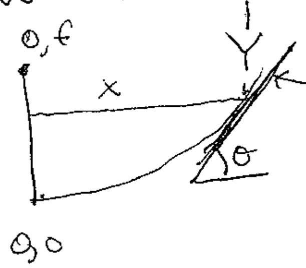
$$x^2 = 4fy$$

$$\boxed{y = x^2/4f}$$

So if the focus for reflected light is at point C, then all rays on axis focus at the same point, all have same optical path length ∞ to f & the image is perfect for a incoming beam || to the optical axis.

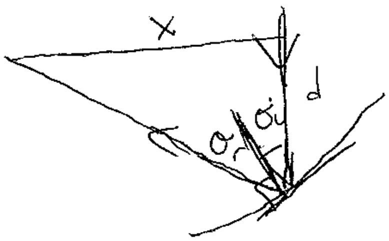
Now must demonstrate that point C is the focus.

must show $\theta_i = \theta_f$ for reflection off surface for a paraboloid



← tangent to surface

$$\tan\theta = \frac{dy}{dx} = \frac{x}{2f}$$



$\theta_i = \theta_r$

Find d: $\frac{x}{d} = \tan(2\theta)$

$$\tan 2\theta = \frac{2\tan\theta}{1-\tan^2\theta} = \frac{x/f}{1 - x^2/4f^2}$$

$$d = \frac{x}{\tan 2\theta} = \frac{x\,(1-x^2/4f^2)\,f}{x} = f - \frac{x^2}{4f} = f - y$$

Hence $f = d + y$, and so focus is at f.

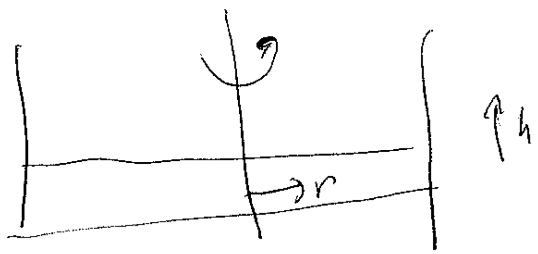
Thus we have a perfect image for an on axis point.

This is valid ONLY for an beam ∥ to the optical axis.

Off axis images become bad quickly.

Telescope design ≡ the art of taking the basic paraboloid + trying to get a larger field with good off axis images.

Note that the equilibrium shape of a rotating confined fluid is a paraboloid



$$\frac{dh}{dr} \propto \text{pressure} \propto \frac{v^2}{r} \propto \omega^2 r$$

$$\boxed{h = a\,\omega^2 r^2} \qquad \text{parabola}$$

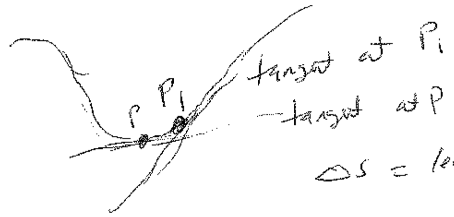
So liquid mercury telescope proposed.

Small prototype constructed by a Canadian group.

Oct 2014

Radius of curvature pg 162

best fit sphere to a curve at point x, y



Δs = length of arc P to P_1

$\Delta\theta$ = angle turned by tangent line from P to P_1

radius of curvature = 1/curvature

Curvature of arc P to P_1 = $\dfrac{\Delta\theta}{\Delta s}$

for P, P_1 straight line, curvature $= 0$ since $\Delta\theta = 0$

$$\text{curvature at } P = K = \lim_{\Delta\theta \to 0} \left(\frac{\Delta\theta}{\Delta s}\right) = \frac{d\theta}{ds}$$

chain rule: $$\frac{d\theta}{ds} = \frac{d\theta}{dx}\,\frac{dx}{ds}$$

$$\tan\theta = \frac{dy}{dx} \qquad \text{So } \theta = \arctan\left(\frac{dy}{dx}\right)$$

$$\text{So } \frac{d\theta}{dx} = \frac{d}{dx}\left[\arctan\left(\frac{dy}{dx}\right)\right] = \frac{\frac{d}{dx}\left(\frac{dy}{dx}\right)}{1+\left(\frac{dy}{dx}\right)^2} = \frac{\frac{d^2y}{dx^2}}{1+\left(\frac{dy}{dx}\right)^2}$$

$$\text{also need } \frac{dx}{ds} = \frac{1}{(ds/dx)} = \frac{1}{\sqrt{1+\left(\frac{dy}{dx}\right)^2}}$$

$$\text{this yields } K = \frac{d\theta}{ds} = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}$$

$$R_c = \frac{1}{K} = \frac{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}{d^2y/dx^2}$$

Radius of Curvature pg 2/2 Oct 2014

Check for a sphere / circle

$$y = \sqrt{a^2 - x^2}$$

$$\frac{dy}{dx} = \frac{-x}{\sqrt{a^2 - x^2}}$$

$$\frac{d^2y}{dx^2} = -\frac{a^2}{(a^2 - x^2)^{3/2}}$$

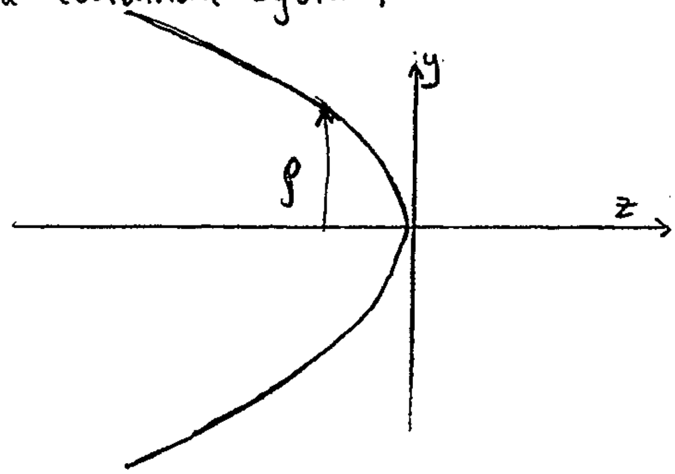
$$R = \frac{\left[1 + \frac{x^2}{a^2 - x^2}\right]^{3/2}}{-a^2 / (a^2 - x^2)^{3/2}} = \frac{\left[a^2 / (a^2 - x^2)\right]^{3/2}}{-a^2 / (a^2 - x^2)^{3/2}} = -a$$

radius of curvature for a sphere / circle $= a$

Brief Introduction to Telescope Optics

Telescope optics are conic sections; the form that focuses light perfectly for any on-axis ray is a paraboloid.

Adopt a coordinate system:



(x is ⊥ to plane of the paper)

A general conic section has

$$y^2 - 2Rz + (1-e^2)z^2 = 0$$

where R = radius of curvature at the vertex

e is the equivalent of the eccentricity of an ellipse, where $e^2 = -K$

e.g., Sphere: $e=0$, $K=0$
Paraboloid: $e=1$, $K=-1$
Hyperboloid: $e>1$, $K<-1$

The equation to describe the surface of revolution is then $\rho^2 - 2Rz + (1+K)z^2 = 0$; $\rho^2 = x^2 + y^2$ (distance from axis, on surface)

The "local" radius of curvature, at any point on the mirror surface, is $r = R[1 - K(\rho^2/R^2)]^{3/2}$.

We can then calculate the focal length of a mirror with an arbitrary conical-section surface (you can find the derivation in Schroeder, "Astronomical Optics")

$$f = \frac{R}{2} - \frac{(1+K)\rho^2}{4R} - \frac{(1+K)(3+K)\rho^4}{16R^3} - \cdots$$

Note that a ray impinging on any point of a mirror conical surface will focus to the same point <u>only</u> if $K = -1$, a paraboloid.

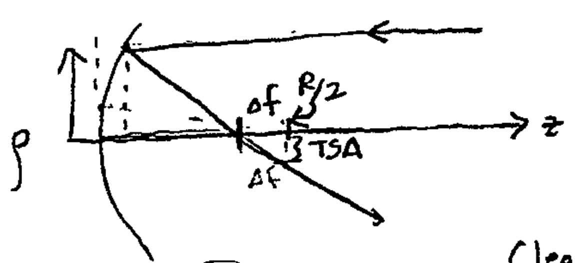
For any other conic, surface, the change in focal length as a function of ρ is

$$\Delta f = f(\rho) - f(\text{paraxial}) = -\frac{(1+K)\rho^2}{4R} - \frac{(1+K)(3+K)\rho^4}{16R^3} - \cdots$$

$\Rightarrow$ <u>blurring</u> <u>of</u> <u>images</u>

This type of on-axis aberration is called "spherical aberration". Many telescopes in the 1930-1980 time span were made w/ parabolic primaries to avoid this problem. [but paraboloids have problems off-axis]

"<u>transverse</u> <u>spherical</u> <u>aberration</u>" is the broadening of images that results from the change in focus vs. ρ:



$$\text{TSA}/\Delta f = \frac{\rho}{(f-z)}$$

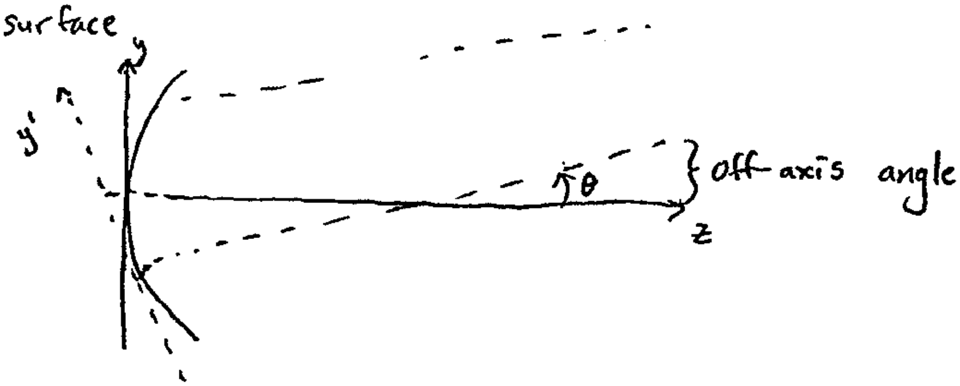
$$\text{TSA} \simeq -(1+K)\frac{\rho^3}{2R^2} \overbrace{-3(1+K)(3+K)\frac{\rho^5}{8R^4}}^{\text{often neglected}}$$

Clearly, the larger the radius of curvature (slower the focal ratio) the less this is a problem.

Off-Axis Aberrations

This refers to aberrations ~~thae~~ aberrations that ~~affect~~ functions of the angle relative to the optical axis – they are what limit the field of view w/ good images in most telescope designs.

The way in which these are calculated is to translate and rotate a parabola to the point on the mirror of interest, at the angle off-axis being considered, and examine the difference between the perturbed parabola and the real surface

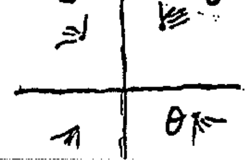


Solve for $2\Delta z$, the amount by which the surface deviates from being "perfect"

This translates into "angular aberration"

$$AA = \underbrace{3a_1 \frac{y^2\theta}{R^2}}_{\text{Coma}} + \underbrace{2a_2\, y \frac{\theta^2}{R}}_{\text{Astigmatism}} + \underbrace{a_3\, \theta^3}_{\text{distortion}}$$

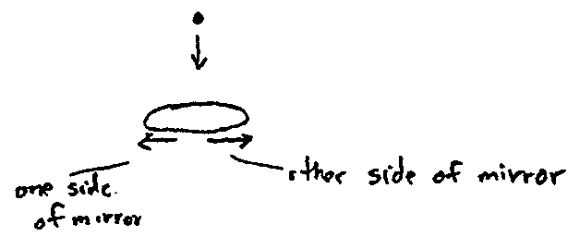
Coma ↓ Changes in sign when θ changes in sign



Coma looks like "comets" with "heads" at the paraxial focus

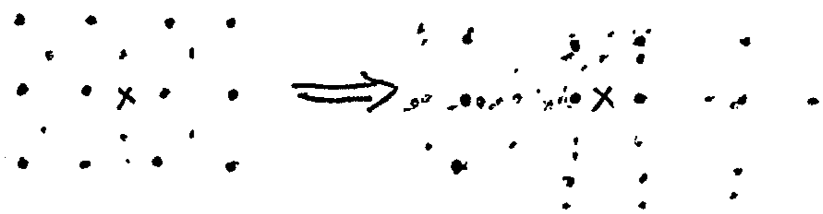
⇒ Limits useable field

<u>Astigmatism</u> $\propto y\theta^2$ so independent of sign changes in θ, but opposite sides of mirror perturb in different directions:



Distortion, being independent of y, does not affect the image quality, but only the way in which the sky is mapped onto the focal plane.

$\Longrightarrow$



These aberrations are of the form $\propto y^n\theta^m$ w/ $n+m=3$

$\Longrightarrow$ "third order aberrations".

Idea in designing optical systems is to minimize or eliminate these aberrations by optimizing parameters.

$\Longrightarrow$ "Correctors"

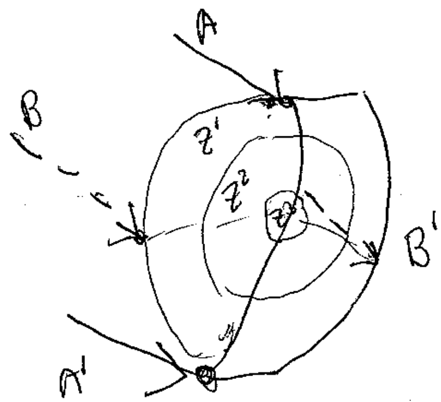
" Complex hyberboloids"

" Multiple mirror systems.

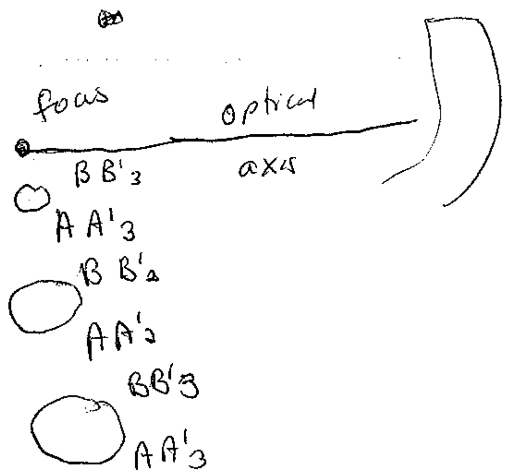
(Also tilt of focal plane + defocus – these are due to incorrect alignment usually.)

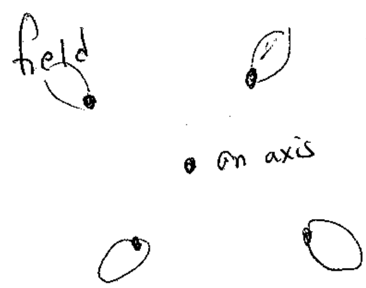
Coma

image defect of off axis / limits angular size of field in good focus



Z^3 is the central area of the aperture





as seen in focal plane

Image shape

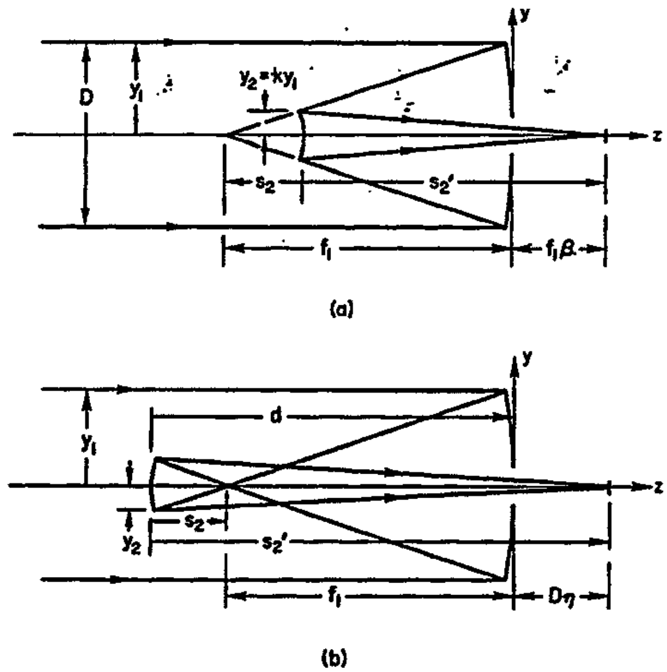
Coma is an image defect ⊥ to optical axis

for a parabola, $\underset{\text{image size}}{\text{coma}} \approx \dfrac{h}{16\,(\text{focal ratio})^2}$

where h is the distance off axis.

(Use this formula to calculate max. field size of a parabola)

Two-Mirror Telescopes



Cassegrain

$f_1\beta \equiv$ "Back focal distance"

Gregorian

Fig. 2.7. Schematic diagrams of two-mirror reflecting telescopes: (a) Cassegrain, (b) Gregorian. Designated parameters are y_1 and y_2, height of ray at margin of primary and secondary, respectively; D, telescope diameter $= 2|y_1|$; $2|y_2|$, diameter of secondary mirror; R_1 and R_2, vertex radius of curvature of primary and secondary mirrors, respectively; s_2 and s_2', object and image distance of intermediate object (located at focal point of primary) measured from the secondary mirror vertex; f_1, focal length of primary mirror; and d, distance from primary to secondary, $d > 0$.

If one uses a paraboloidal primary, and a hyberboloidal secondary, the combination has zero spherical aberration

$$K_p = -1$$

$$K_s = -\frac{(m+1)^2}{(m-1)^2} \quad \text{where} \quad m = \frac{-s_2'}{s_2}$$ (transverse magnification of secondary)

This combination is called a "Classical Cassegrain"

One can then begin with this combination and "tweak" the conic constants K_p and K_s to keep TSA $=0$ and perhaps "cancel out" other aberrations.

The most successful such "tweak", and the one used in most modern multi-purpose, wide field O/IR telescopes, is the Ritchey-Chrétien design.

For the primary, modify the paraboloid to a hyperboloid

$$K_p = -1 - \frac{2(1+\beta)}{m^2(m-\beta)} \quad ; \quad \beta = \frac{D_s}{D_p}(1+m) - 1$$

ratio of secondary to primary diameter

$$K_s = -\frac{(m+1)^2}{(m-1)^2} - \frac{2m(m+1)}{(m-\beta)(m-1)^3}$$

(this hyperboloid is slightly different than that in a classical Cassegrain.

Result?

1. Zero coma to 3rd order
2. Zero spherical aberration
3. Now field size is limited only by astigmatism.

Examples: $\left\{\begin{array}{l}\text{HST}\\ \text{Keck}\\ \text{P60}\end{array}\right.$

"Aspheres"

take the surface, fit a sphere to it in some "best" way, + look at the deviation of the surface from the best fitting sphere.

this is an indication of how difficult the ~~piece~~ surface will be to manufacture.

0.02" (= 0.5 mm) = 1000 waves at 0.5 μ is a difficult asphere.

We will not discuss Optical fabrication, especially for large optics, and testing → this would be a whole lecture or more.

Opticians love spherical mirrors
flat mirrors
everything else is harder!!

Aberration Theory Made Simple,
V. Mahajan, SPIE press

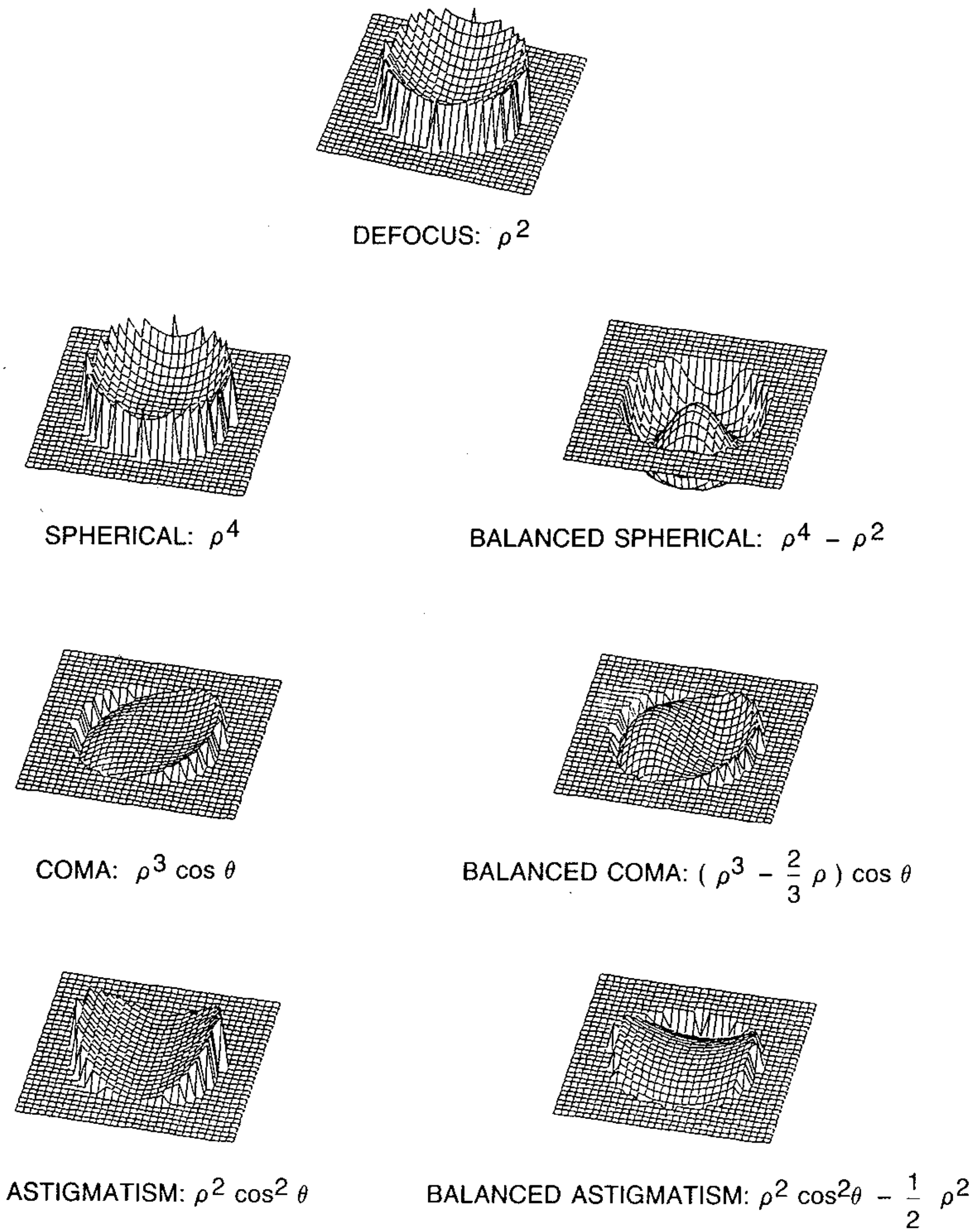


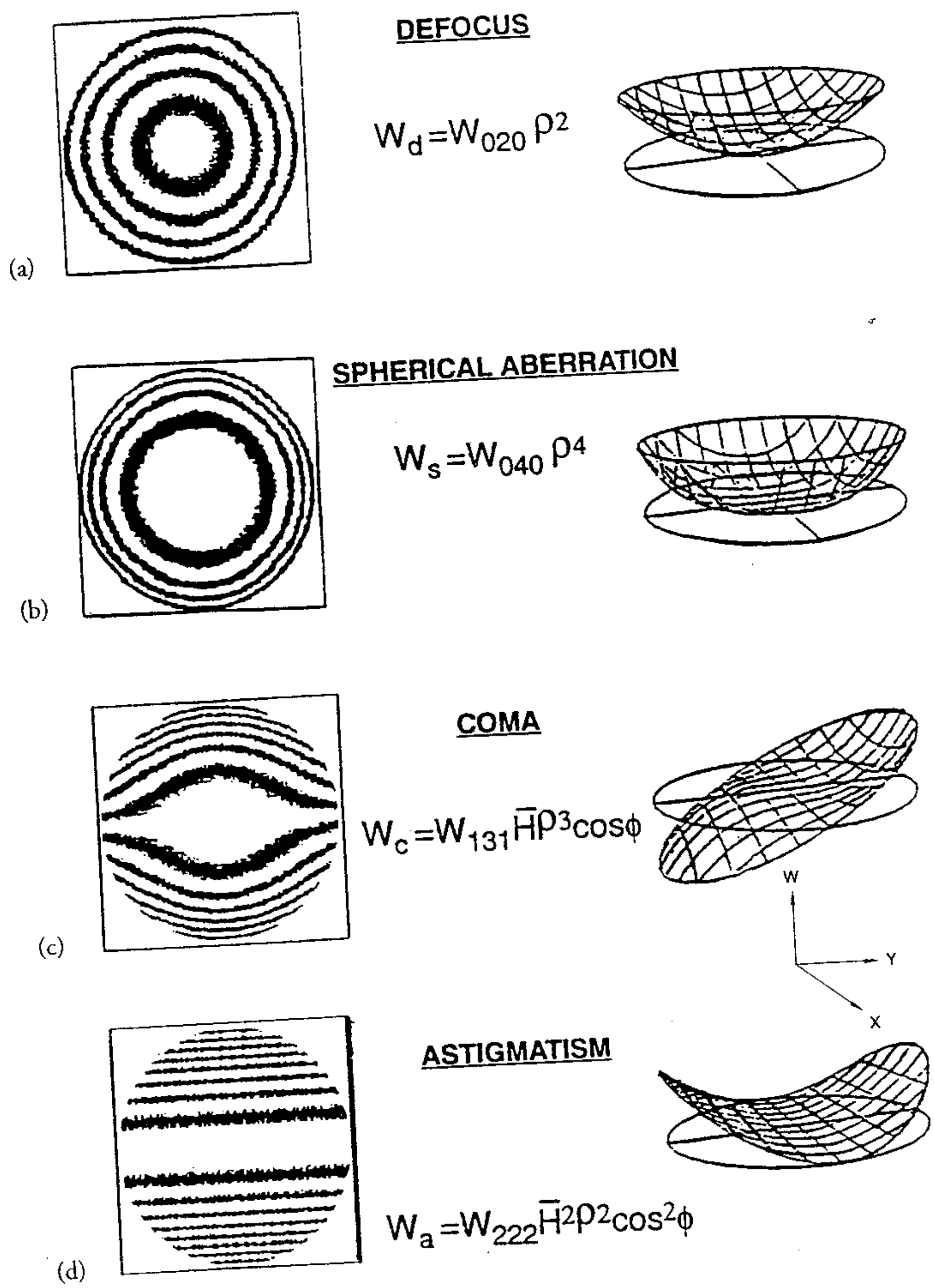
Figure 12–1. Shape of primary aberrations representing the difference between an ideal wavefront (typically, spherical) and an actual wavefront.

, Joseph Geary
SPIE Press

The first eight Zernike polynomials are shown in Fig. 1.11, and described mathematically as follows:

$$W = \sum_i Z_i R_i(\rho) G_i(\phi) \tag{1.6}$$

$\boxed{\text{Seidel Polynomials}}$



Introduction to Wafront Sensors, Joseph Geary
SPIE press

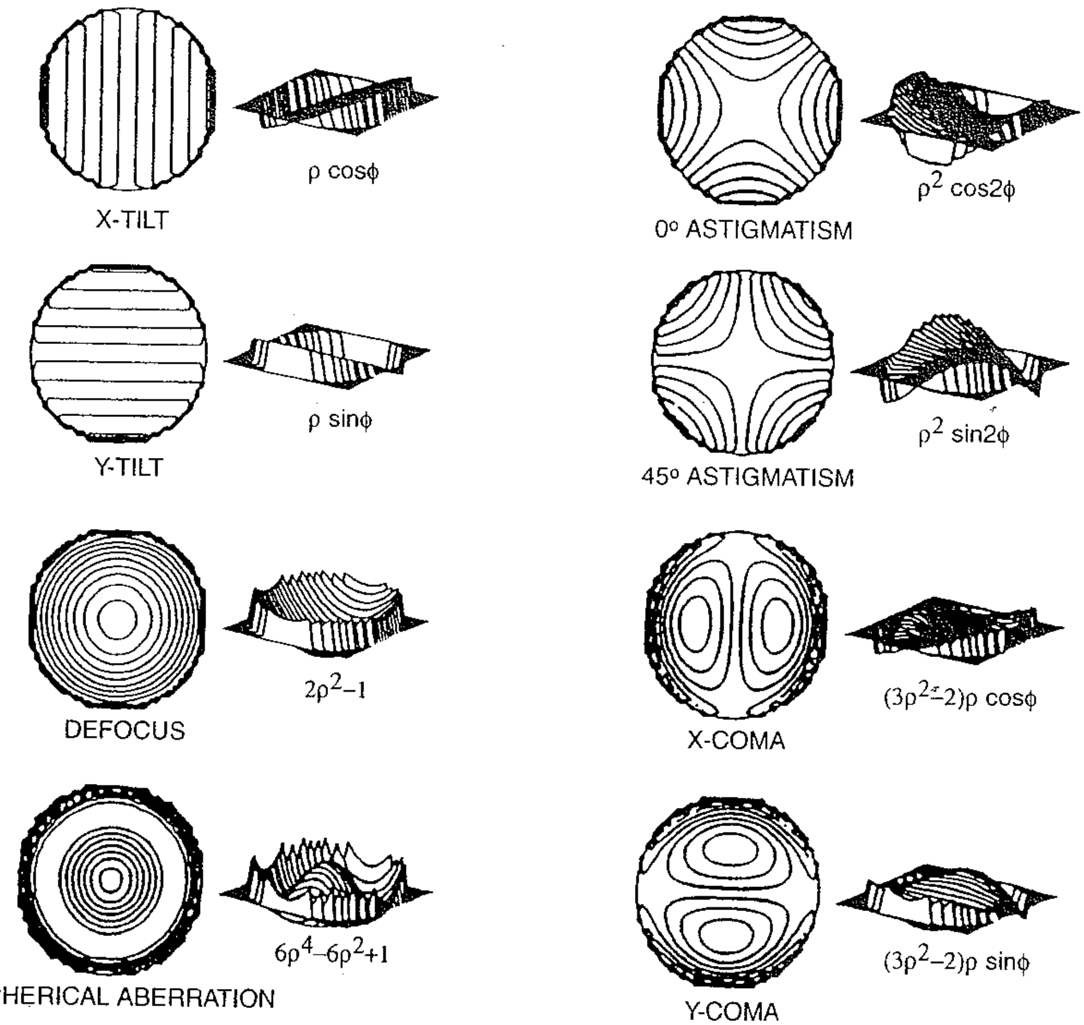


Figure 1.11 The first eight Zernike polnomials. (Ref. 3.)

Like the Seidel polynomials, the Zernike polynomials are normalized. All dimensionality is carried by the coefficients Z_i. One difference for the Zernikes is that the angle ϕ in the exit pupil is measured from the X-axis instead of the Y-axis as it was for the Seidels. Given Zernikes, the Seidel coefficient magnitudes can be generated from the first eight terms (shown above).[3] For example, Seidel spherical aberration is 6 times its Zernike counterpart.

Introduction to Wavefront Sensing -
Joseph Geary
SPIE press

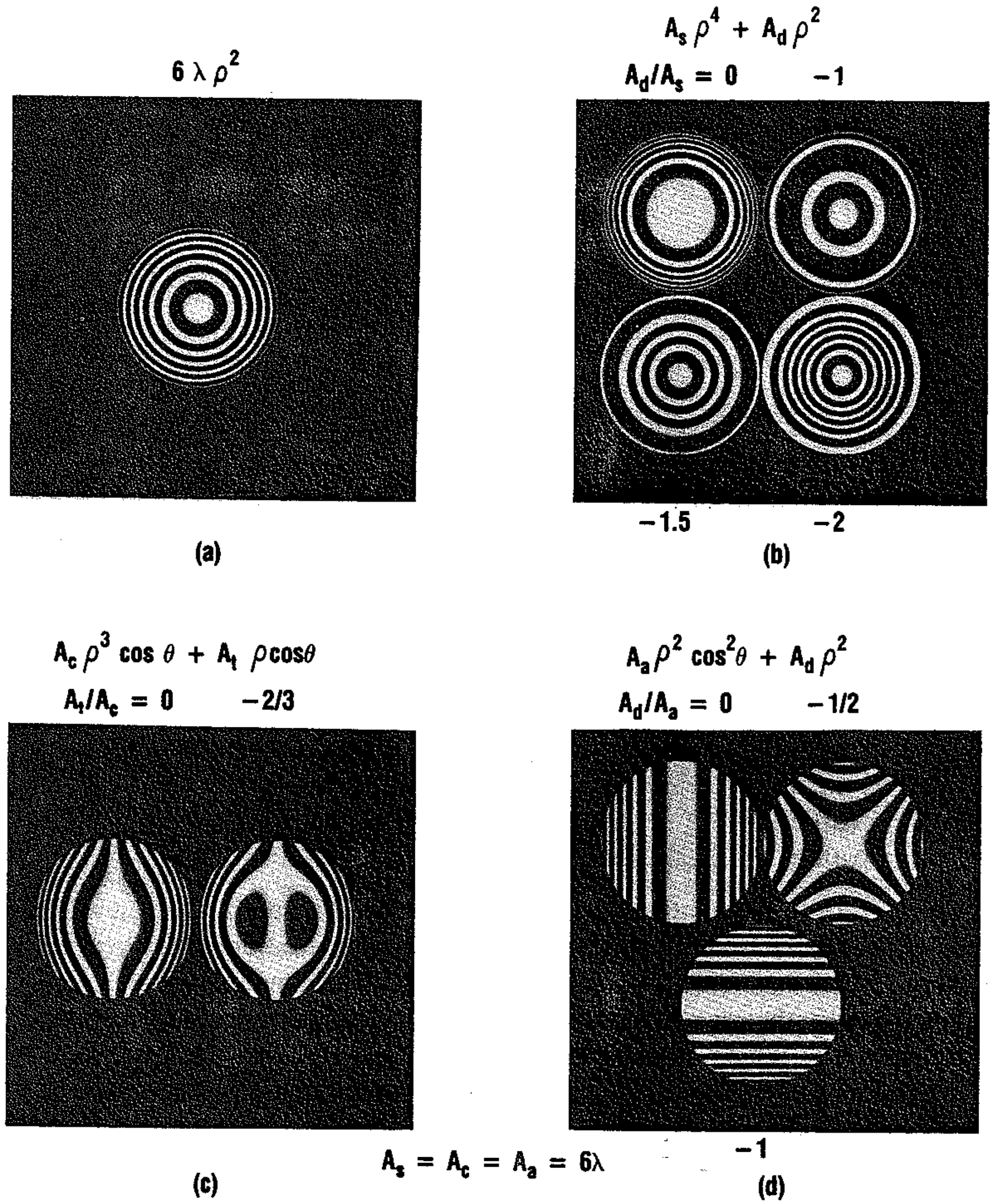
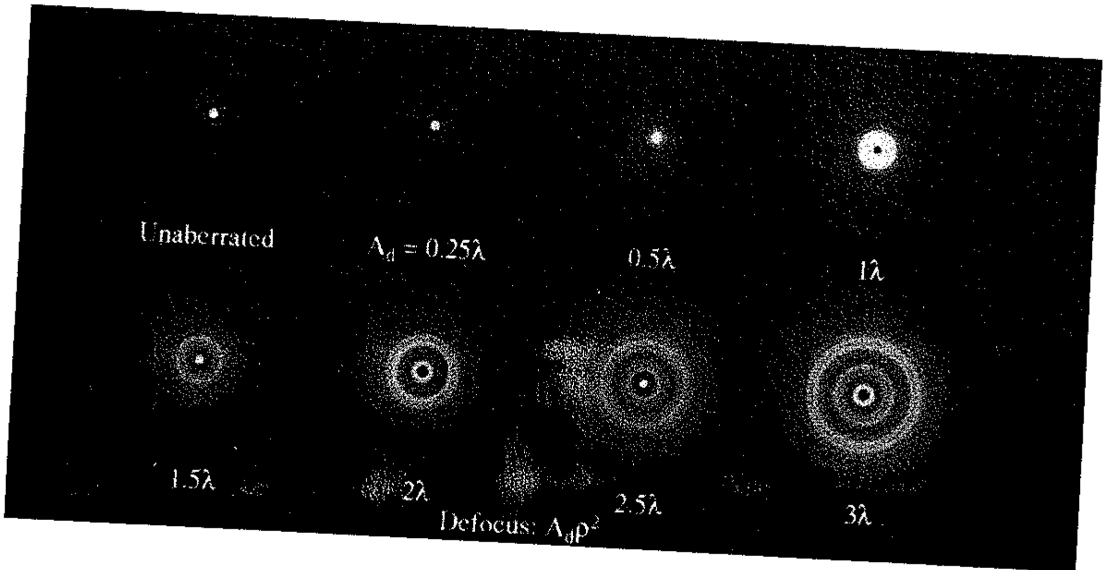
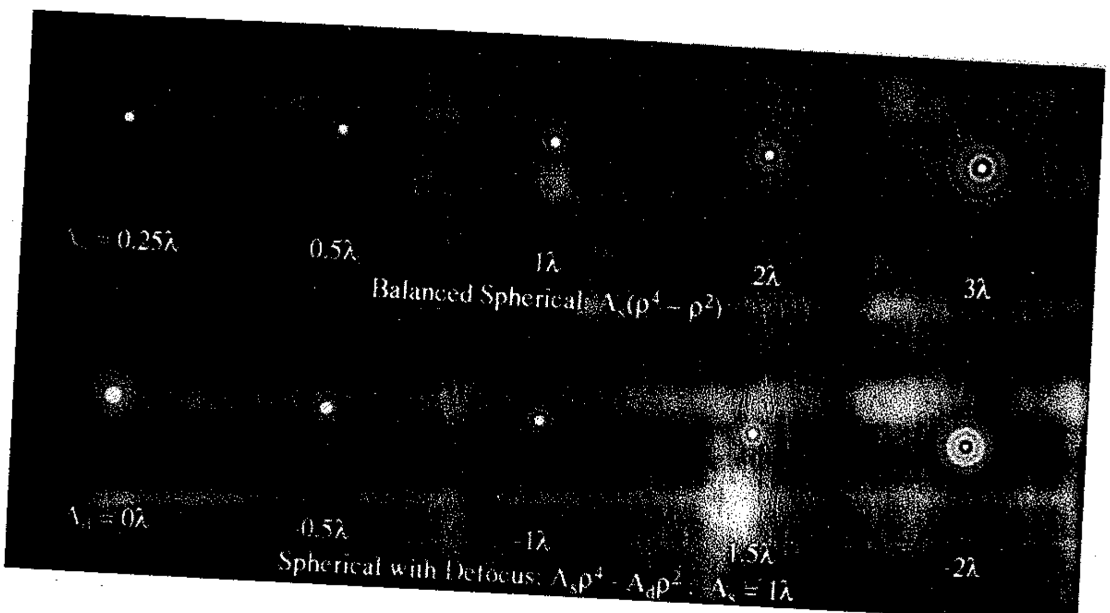


Figure 12–3. Interferograms of primary aberrations: (a) defocus, (b) spherical combined with defocus, (c) coma combined with tilt, (d) astigmatism combined with defocus. The aberrations in the interferograms are twice their corresponding values in the system under test because the test beam goes through the system twice.

Aberration Theory Made Simple
V Mahajan, SPIE press



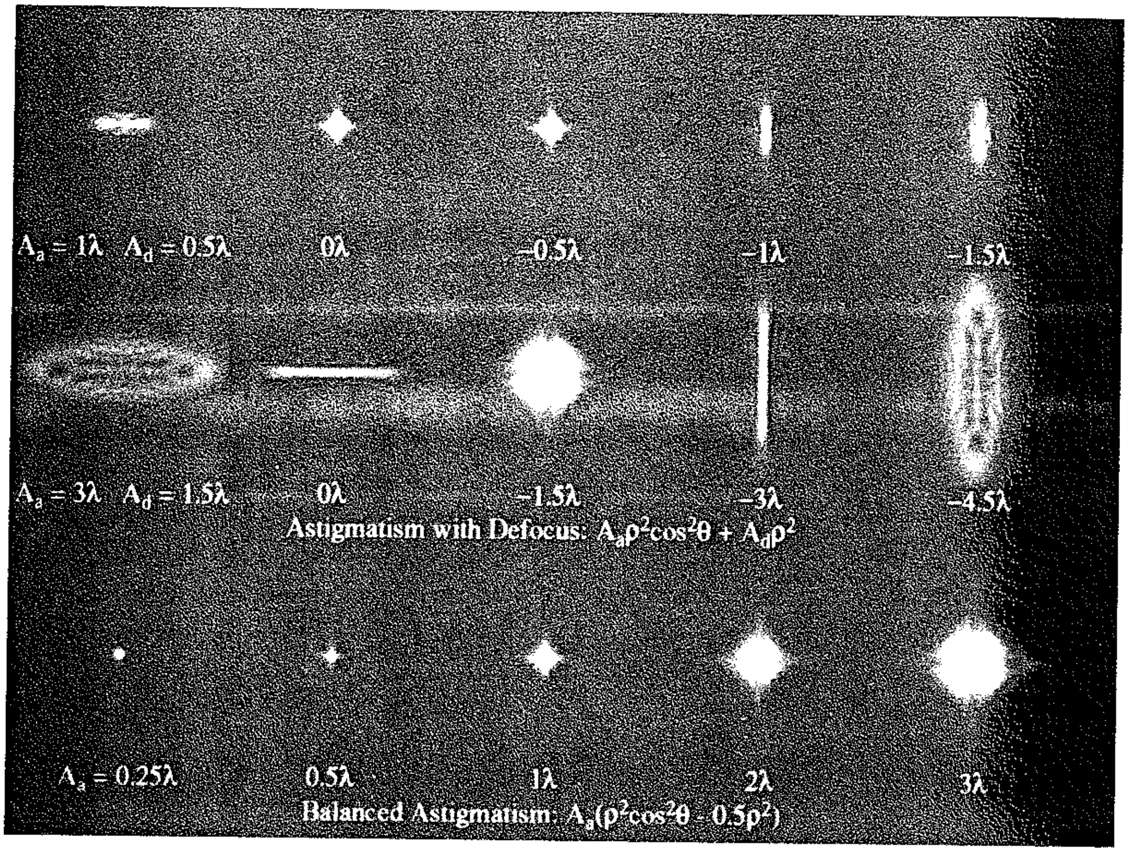
(a)



(b)

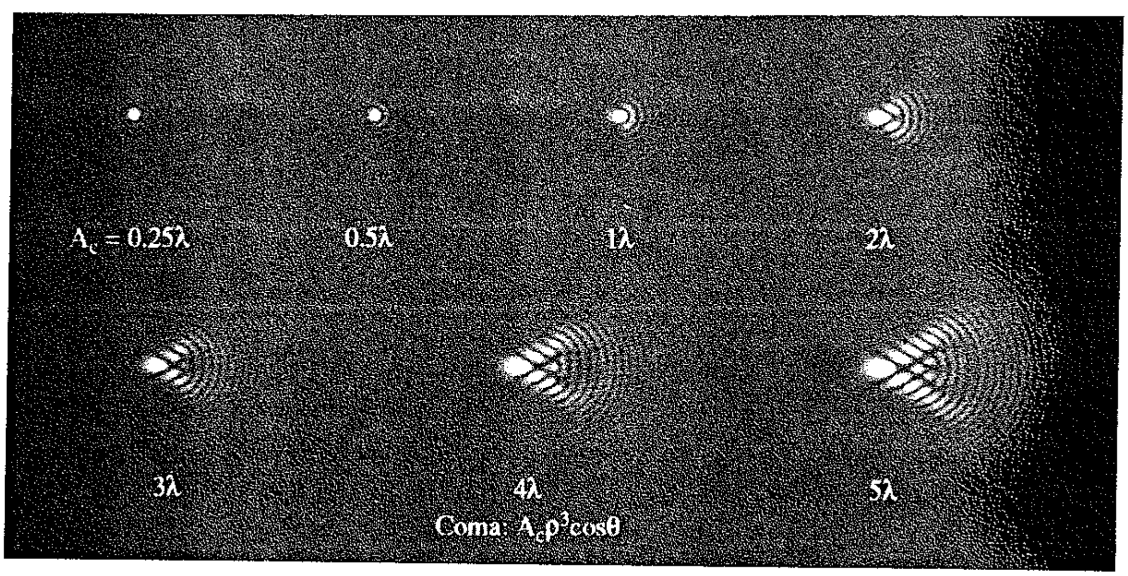
Figure 8–10. Pictures of PSFs for various amounts of (a) defocus and (b) spherical aberrations.

Astigmatism - Various amounts



(a)

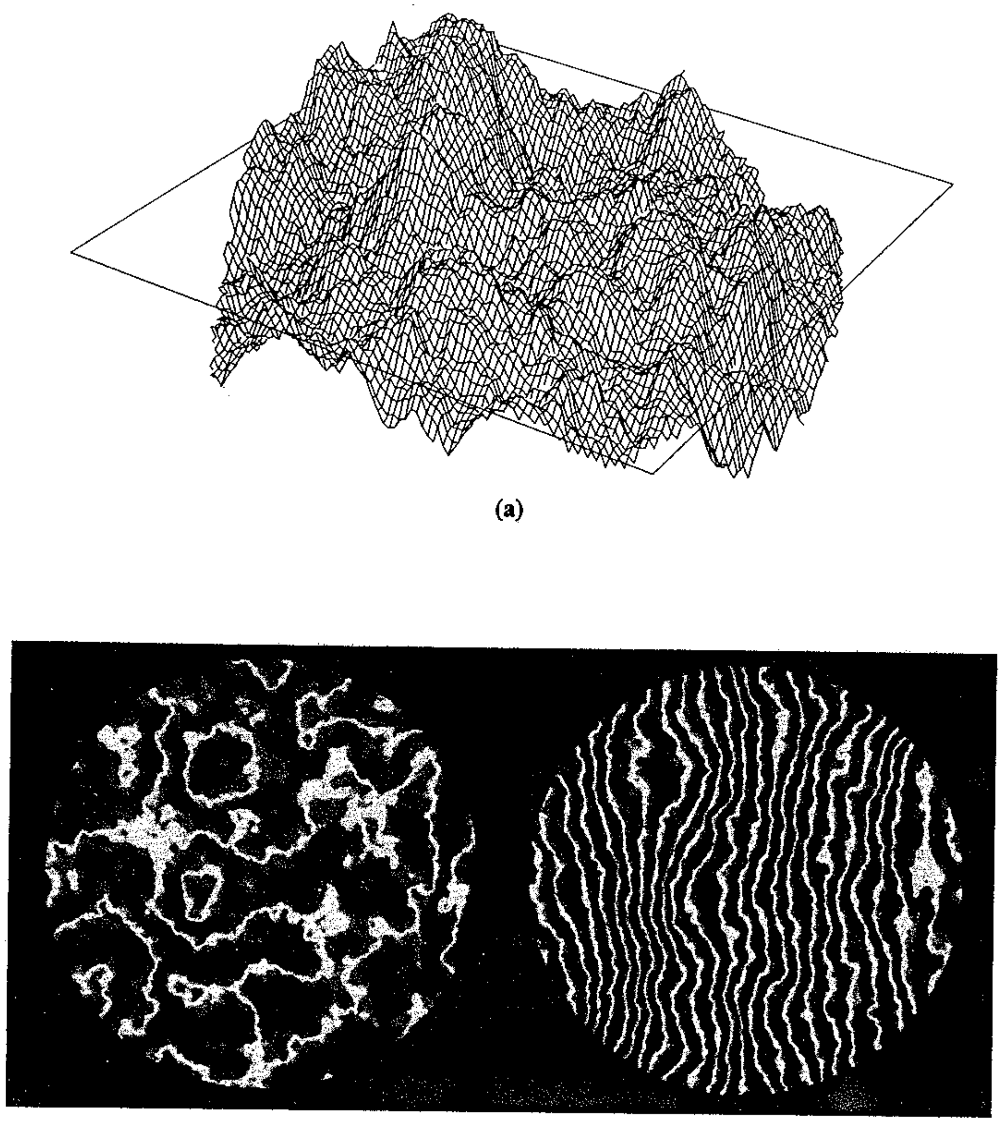
Coma aberration (various amounts)



(b)

Figure 8–11. Pictures of PSFs for various amounts of (a) astigmatism and (b)

Introduction to Wavefront Sensing
J Geary, SPIE press



(a)

(b) (c)

Figure 12-4. **Aberration introduced by atmospheric turbulence corresponding to $D/r_0 = 10$. (a) Aberration shape. (b) Aberration interferogram. The standard deviation of the tilt-free aberration introduced by turbulence is 0.396λ. (c) Interferogram with 25λ of tilt.**

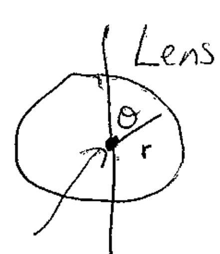
Summary of Mirror + Lens Aberrations

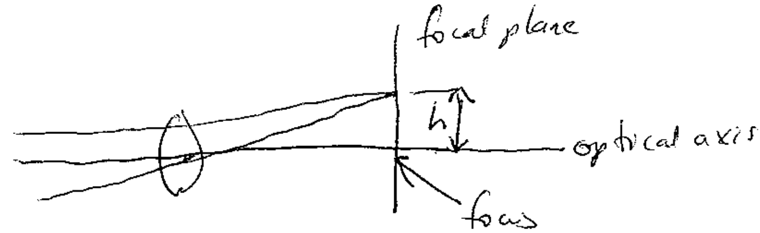
Ray tracing equations used in Gaussian optics are correct only to 1st order in the inclination angle of rays + normals to the surface. They assume thin lenses, $\sin\theta \approx \theta$, etc.

Deviations from Gaussian optics are called lens aberrations.

The true image shape requires exact calculations. Usually its adequate to go to 3rd order in angles.

Primary aberrations are those that can be described by 3rd order theory. Since the transverse aberration is $\dfrac{\partial W(r,h,\theta)}{\partial r}$, where W is the optical path length, r the distance off axis in the lens, h the distance off axis in the image plane.





$$W = OPL(r,\theta) - OPL(r=0)$$

optical path length

ray through center of lens

The order of the aberration is the sum of the powers of h and ρ ($\rho = r/(D/2)$ = radius normalized so lens goes 0 to 1)

for the transverse aberration (+1 when looking at W or OPL)

Given a centered system with rotational symmetry, there are no 2nd order terms in the transverse aberration (homework!)

The only 3rd order terms that exist are 5 terms of the form $_A C_{BC}\, h^A r^B \cos\theta^C$

$$W = {}_0C_{40}\, r^4 + {}_1C_{31}\, h r^3 \cos\theta + {}_2C_{22}\, h^2 r^2 \cos^2\theta$$
$$+ {}_2C_{20}\, h^2 r^2 + {}_3C_{11}\, h^3 r \cos\theta$$

There is no term ${}_0C_{40} h^4$ because rays that go through the center of the lens are not deviated.

The only on-axis ($h=0$) aberration is Spherical ab- ${}_0C_{40}\, r^4$

Coma ${}_1C_{31}\, h r^3 \cos\theta \equiv {}_1C_{31}\, h\,(x^2+y^2)x$

this is $\propto h$, so image is worse off axis.

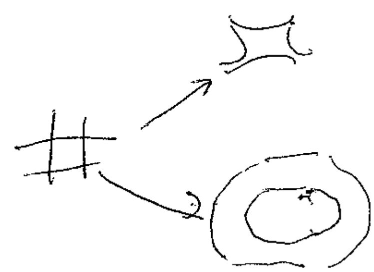
$\left({}_2C_{22}\cos^2\theta + {}_2C_{20}\right)h^2r^2$ is astigmatism + curvature of field.

$${}_3C_{11}\, h^3 r\cos\theta = {}_3C_{11}\, h^3 x$$

$$\frac{\partial W}{\partial x} = {}_3C_{11}h^3$$ (ind. of r and θ), so this is a spatial distortion term. Image is a point, but shifted in the focal plane. Shift $\propto h^3$, so worse off axis.

${}_3C_{11} > 0$ ~~pincushion~~ pincushion

< 0 barrel



The 5 terms listed above represent the <u>ONLY</u> terms that occur in 3rd order theory of centered, aligned systems. (ignoring manufacturing defects, design errors...)

Other low order terms represent defocus ($W = A_d\,\rho^2$) and tilt ($W = A_t\,\rho\cos\theta$) which are not present if the system is designed and aligned correctly.

A good optical design has values of all ${}_AC_{BC}$ which are acceptable to the end user within the desired field of view and over the design wavelength range. "Acceptable" must be defined with the application + user in mind.

Schmidt Telescope

If you want/need an <u>extremely</u> wide field (i.e. degrees) what can you do?

Answer: start with spherical primary as this has no off-axis aberrations, just spherical aberration

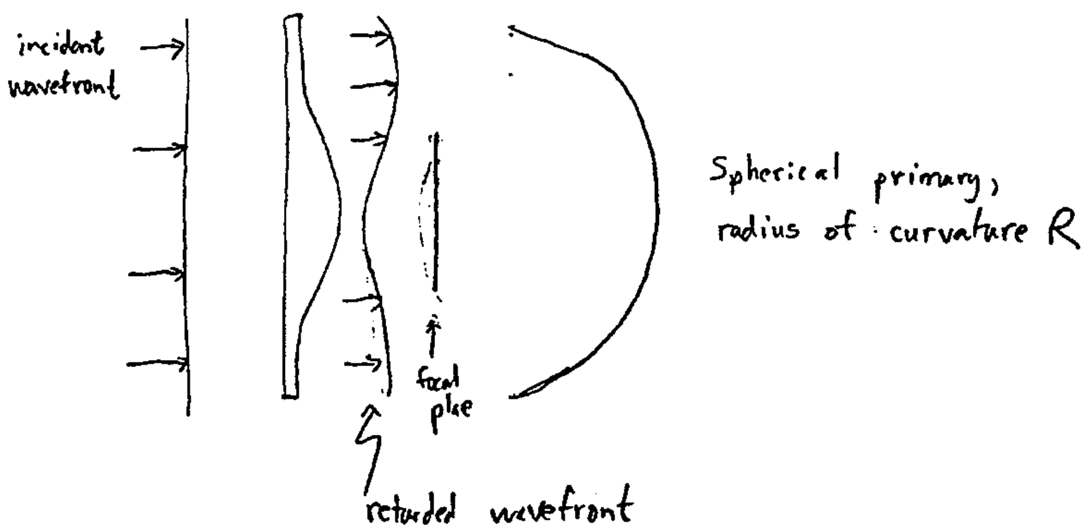
Add a corrector for spherical aberration →

Schmidt telescope

Pal 48" Schmidt telescope – used for Palomar Sky Surveys and now for Palomar Transient Survey

Schmidt telescope

The basic idea:

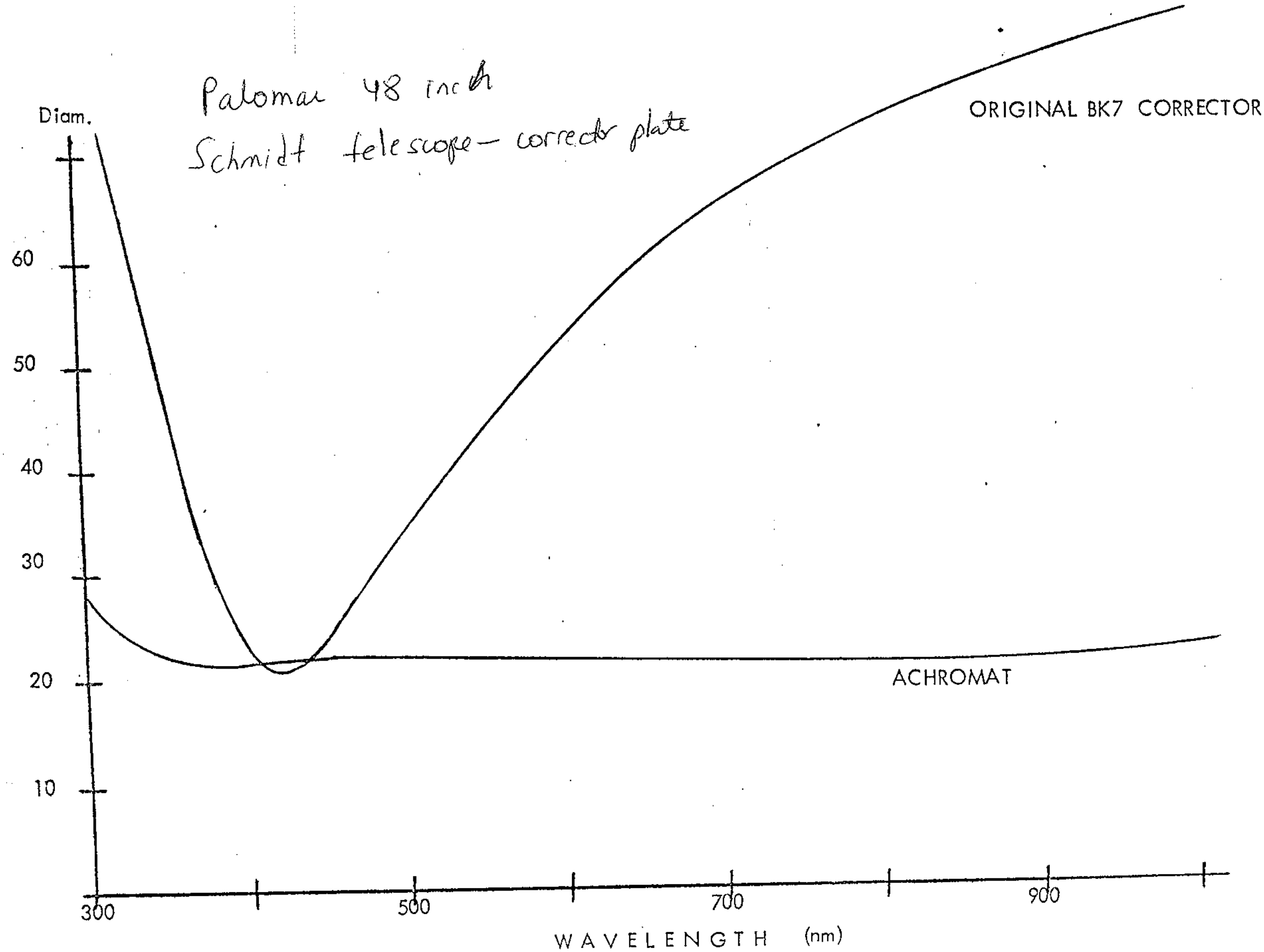


The wavefront is retarded by exactly enough to cancel out the difference in focus vs. ρ axis that is introduced by spherical aberration.

Problems:
- "Camera" itself occults the primary
- Focal surface is spherical (not a huge problem)
- Corrector is difficult/expensive/heavy and has residual chromatic aberration (but re-focus vs. band can get around this problem).

e.g.
- Palomar 48" Schmidt / UK Schmidt ~6° FoV.
- Spectrograph cameras (e.g.

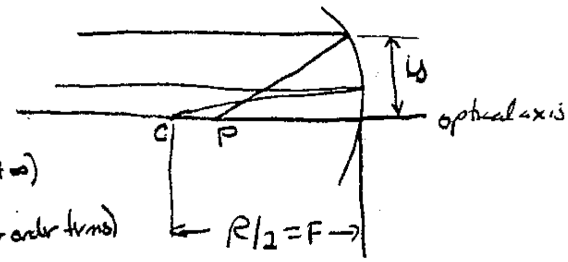
Palomar 48 inch
Schmidt telescope — corrector plate



Schmidt Camera

Article by Bowen in Telescopes (chapter 4)

Spherical mirror, radius of curvature R.



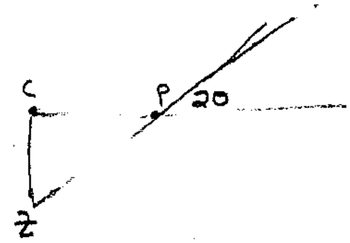
Then spherical aberration –
(but only spherical aberration,
since mirror same for ever point source at ∞)

$$CP = \frac{R}{2} - F(h) = \frac{(1+K)\,y^2}{4R} \text{ (+ higher order terms)}$$

previously derived for a general conic reflector.

$K = 0$ sphere

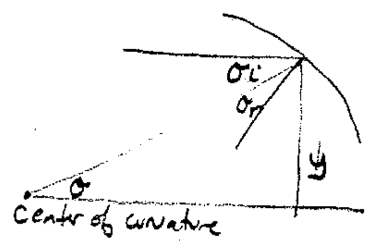
$CP = y^2/4R$



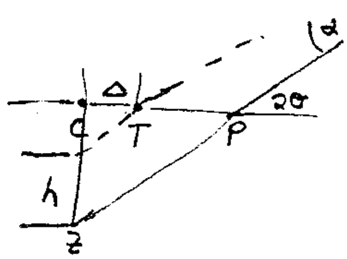
$CZ = CP(\tan 2\theta)$

$= CP(2\tan\theta) = CP\,2\theta$ (small angles)

$= CP\left(\frac{2y}{R}\right) = \frac{y^3}{2R^2}$



For all rays,
Try to achieve a compromise focus T, slightly toward mirror from C.



α = correction angle needed to get ray to focus at T

$= h/(R/2)$

$$h \approx [CP - \Delta]\tan 2\theta = \left(\frac{y^2}{4R} - \Delta\right)\frac{2y}{R}$$

Set $F = R/2$

$$\alpha = \left(\frac{y^3}{2R^2} - \frac{2y\Delta}{R}\right)\Big/(R/2) = \frac{y^3}{R^3} - \frac{4y\Delta}{R^2} = \frac{y^3}{8F^3} - \frac{y\Delta}{F^2}$$

5B

We put a thin prism across the aperture to deviate the beam to achieve better focus.

Corrector plate index n thickness $t(h)$

$$\alpha = (n-1)\frac{dt}{dh} \qquad (t = \text{constant, no deviation})$$

$$\frac{dt}{dh} = \frac{\frac{h^3}{8f^3} - \frac{\Delta h}{f^2}}{(n-1)}$$

$$t = \frac{\frac{h^4}{32f^3} - \frac{\Delta h^2}{2f^2}}{(n-1)} + K \qquad h^2 dh$$

4th order curve hard to make

R = aperture of corrector plate (radius, Diameter) D

$u = \frac{h}{R}$ new variable

$\frac{f}{D}$ focal ratio $= F$

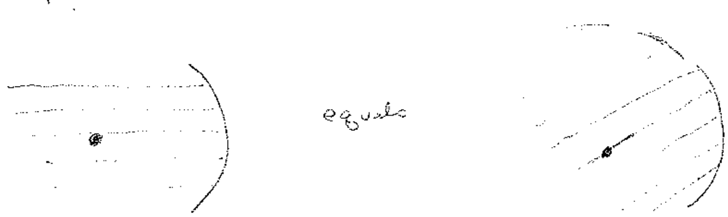
$\Delta = \frac{aD}{64F}$

$$t = \frac{(u^4 - au^2)}{512(n-1)F^3} + K$$

4th order curve hard to manufacture.

Resulting focal plane is curved – plates must be bent to fit.

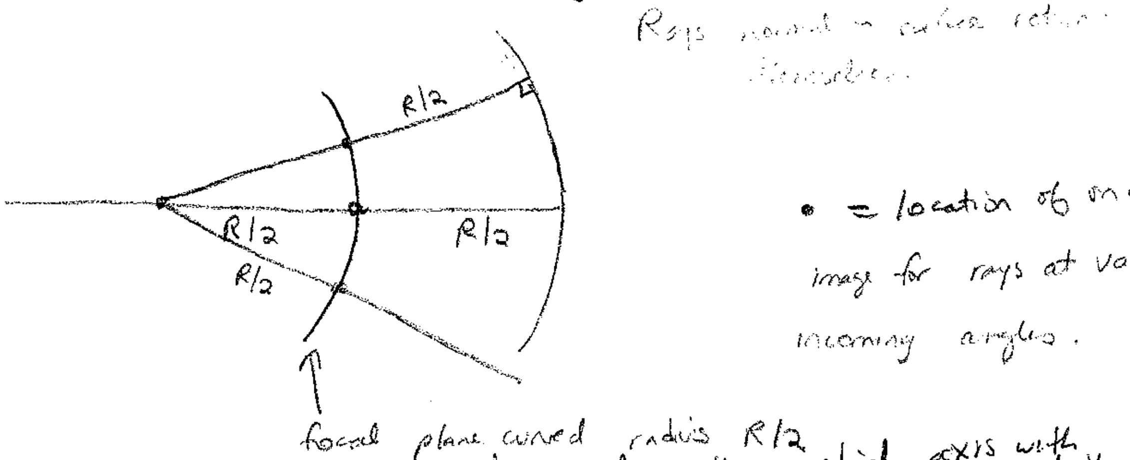
Spherical mirror has no off axis aberrations – (No unique axis of symmetry)



Schmidt telescope has very small off-axis aberrations due to fact that corrector has an axis of symmetry. (note that spherical mirror itself – all orientations are on axis, so only spherical aberration).

Schmidts – continued

Note that FL $\simeq R/2$ – Ignore corrector



• = location of on axis image for rays at various incoming angles.

The location of the corrector along the optical axis with respect to the primary is defined by minimizing the required thickness of the corrector on axis.

Problem of chromatic effects introduced by corrector lens.

Original P48 corrector lens designed for 4200A

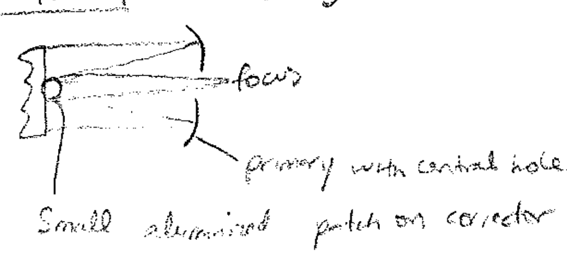
Size of images at other $\lambda \propto \dfrac{n(\lambda)-1}{n(4200A)-1}$

$\dfrac{n(\lambda)-n(4200A)}{n(4200)-1}$		$\lambda_{min} - \lambda_{max}$ (Crown glass)
± 0.01	(.99 to 1.01)	3850 – 4960
± 0.02		3520 – 6040
± 0.03		3260 – 8000A.

IR + UV images poor.

New corrector – Cemented achromatic doublet. New sky survey.

Maksutov telescope – Cassegrain Schmidt



All modern telescopes designed with ray tracing programs – Spot diagrams calculated as f(λ, distance off axis)

Compromised Spectroscopic Only Telescopes

Compromise performance to significantly reduce cost for a given aperture

Sacrifice

a) image quality (ok for spectra, too poor for direct images)

b) ability to point anywhere on sky (objects must/can be observed only in certain parts of the sky, restricts ~~for~~ maximum integration time)

LAmost
Spectroscopic telescope

(China)

Ma 5.7×4.4 m
24 Segments

Mb 6.7×6.1m
37 segments of a spherical mirror
Fixed

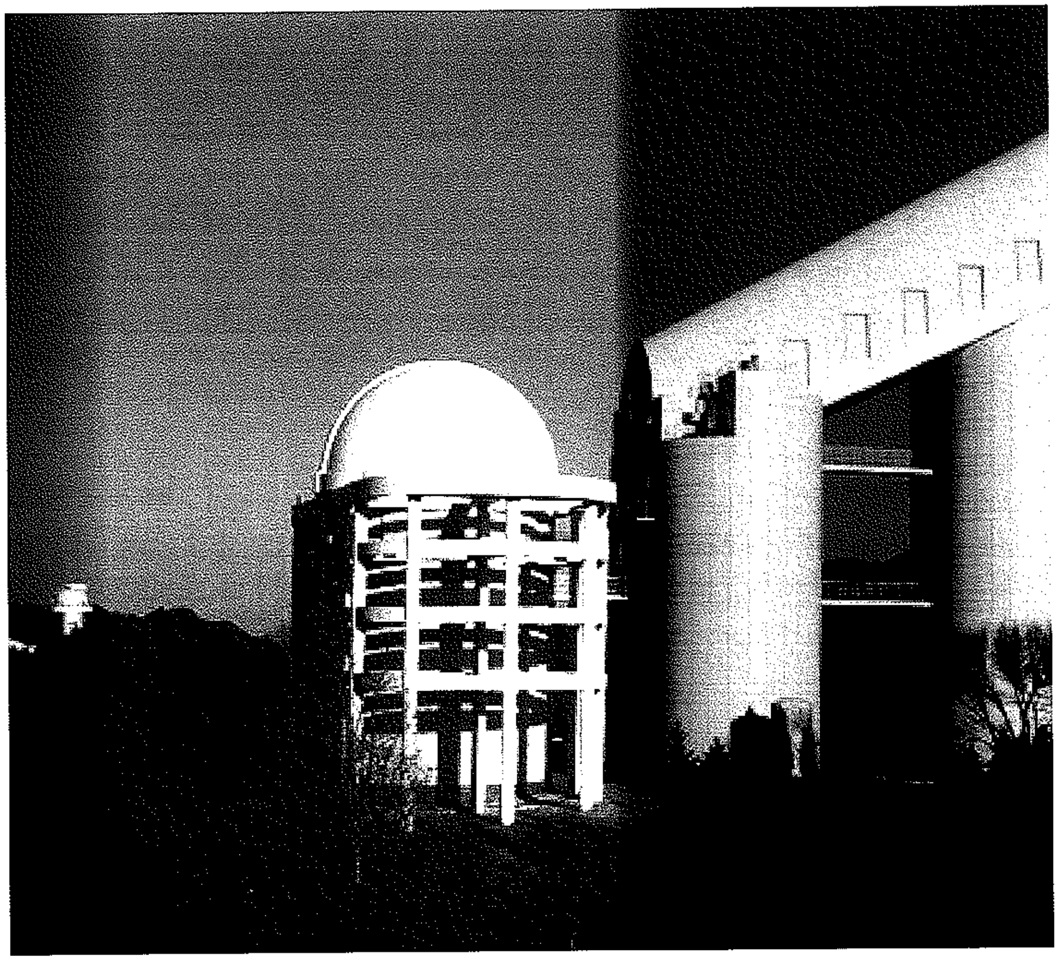
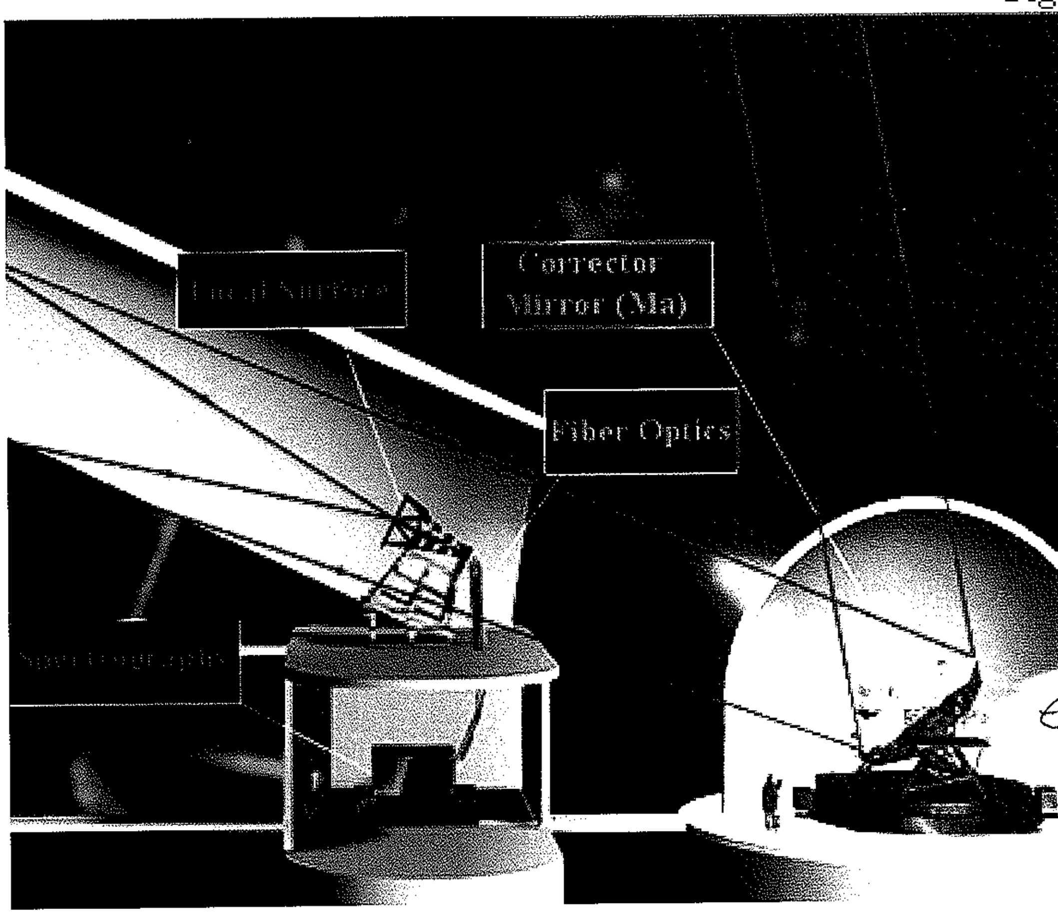


Figure 1 LAMOST

FL 20 m
FOV 1.75m diameter
feeds 16 spectrographs
via 4000 fibers

Can observe only near the meridian

Images have lots of aberrations, but does not (should not) matter for fiber spec.



Ma

Figure 2 LAMOST overview

HET (Hobby - Ebberly Telescope) (1st light 1996)
McDonald Obs, Texas

→

South African Large Telescope (SALT) (1st light 2005)
$\boxed{\text{Only Spectroscopy}}$ (big fiber fed spectrographs)

SALT: Spherical primary made of hex segments
fixed elevation, primary rotates on a turntable
but not in altazimuth (alt/az, but only az).

elevation 53°
aperture 11 m x 9.8 m (91 1m hexagons)

Complex tracker / + instrument 13 m above mirror, object illumination
aberration corrector
Sweeps across mirror as Earth rotates.

Complex observation planning / use in queue mode /
pre-scheduled

Illuminated area on primary not constant
during a long exposure

Can only track object for an hour or two

An optical telescope similar to the Arecibo
Radio telescope.