Topic 6: Optical Systems

Aim: To apply the image formation theory to basic real optical systems and how they are designed.

Contents:

1. Basic Design Criteria.
2. Available lens types and materials.
3. Ray Tracing
4. Evaluation of ray tracing.

Design Criteria

Aim of Lens Design is to form a system that has “sufficiently good” performance in a given geometry.

There are no **universal** solutions, but a range of good solutions have been developed over the last 100 years.

Before you start designing a system you need consider:

- Numeric Aperture (or F_{No}).
- Field angle.
- Range of wavelength (mono or poly chromatic).
- Location on object and image planes.
- Quality needed.
- Cost and complexity allowable.

Use this information to look-up the “Type of Lens” you will need.

(Don’t want to use a 7 element lens when a 2 element will do).

The aim of lens design is to cancel the aberrations with combinations of lenses, mirrors and (perhaps) holograms.

System Types

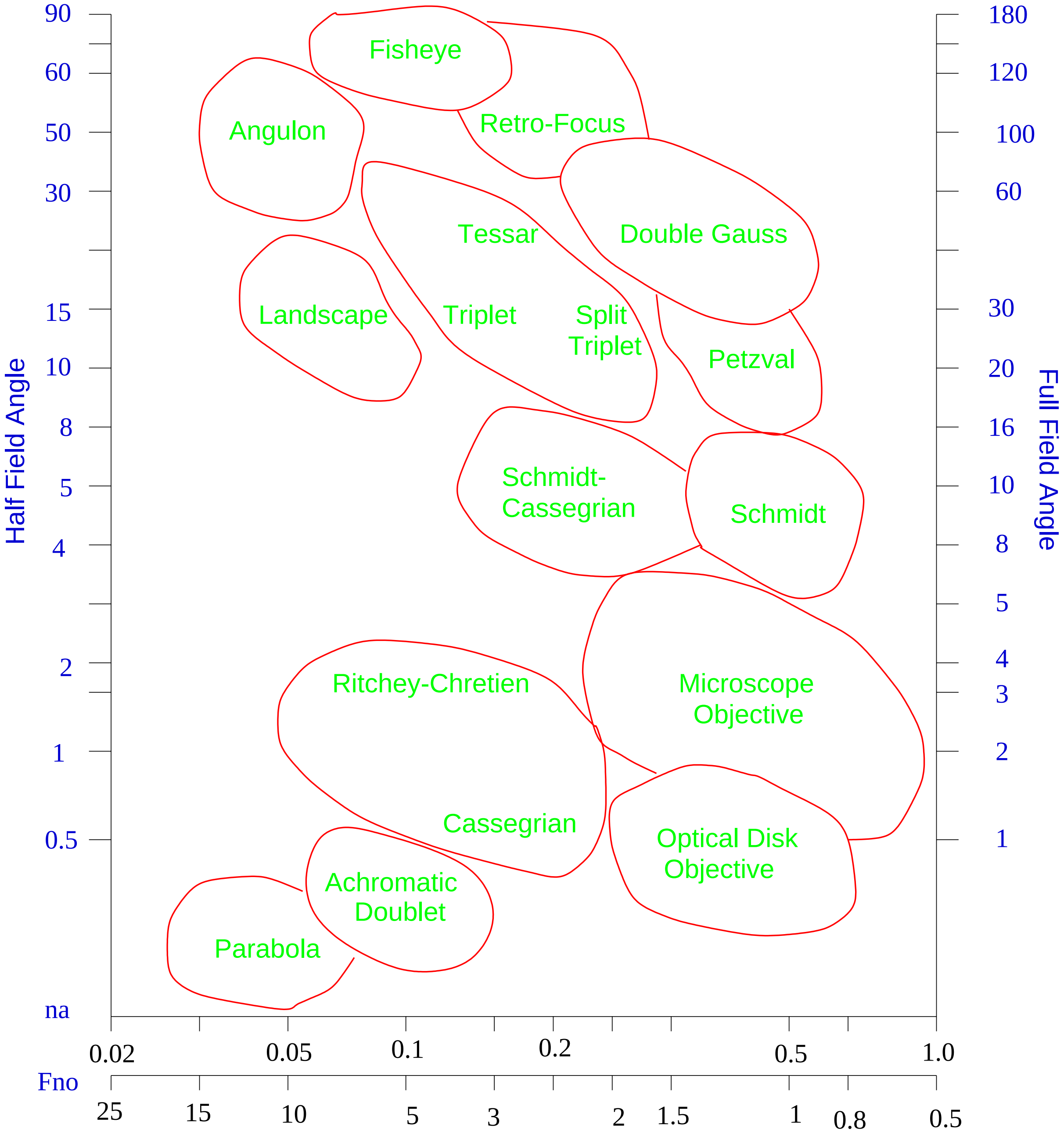
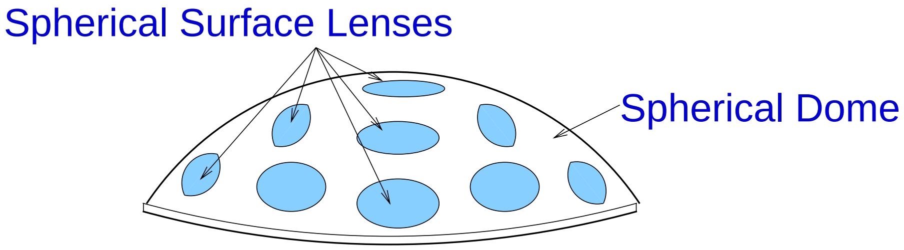


Diagram of system types for various ranges of F_{No} and *Field Angle*, (from *Modern Lens Design*, WJ Smith, Academic Press)

Lens Types and Materials.

95% of optical surface are spherical and 99% of optical systems are "on-axis" (cylinderically symmertic). **Why?**

1. Spherical surface are easy to make by polishing.
2. Design with spherical surfaces well developed.
3. On-axis easy to design and make.



Mass produce spherical surfaces, convex surfaces on a "dome", concave on a "depression".

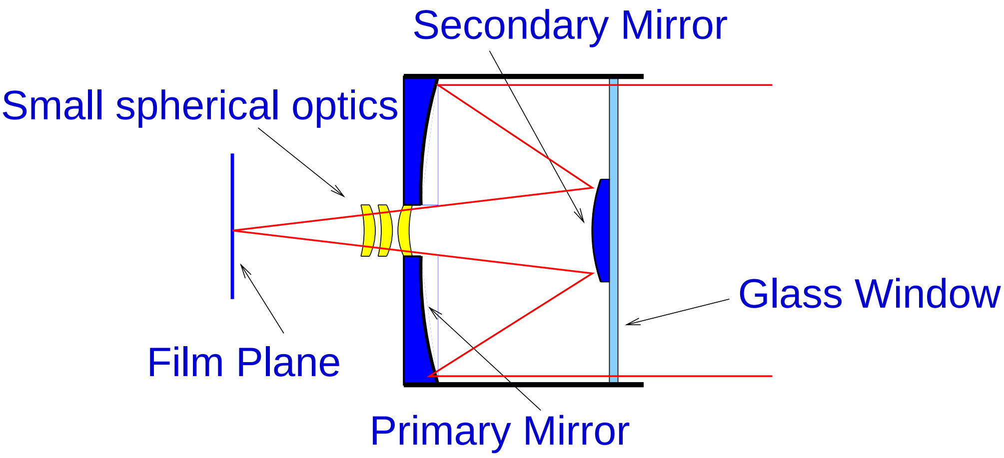
Accurate surfaces, but less control on lens thickness.

Other Types

Other surfaces possible, these include

Reflective Surfaces:

1. No dispersion, (any wavelength).
2. Folded or “off-axis” optical systems.
3. Results in “short” system.
4. Relatively expensive.
5. Easy(ish) to make very large (4 m diameter mirrors have been made).
6. Mixed reflective/refractive system.

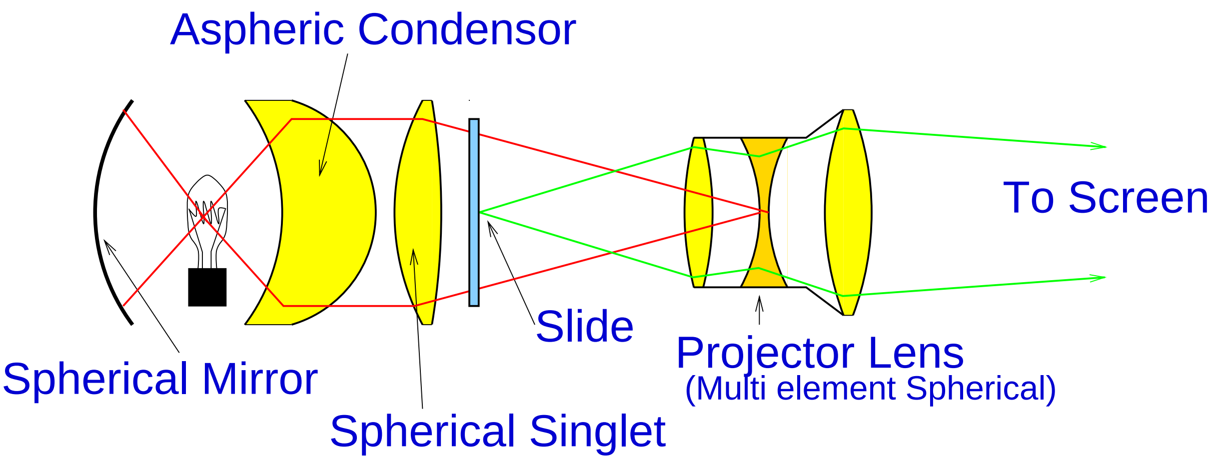


Long focal length “mirror” type camera lens, (1000 mm). Two mirrors, (usually slightly aspheric).

Used extensively in large telescopes.

Aspheric Surfaces:

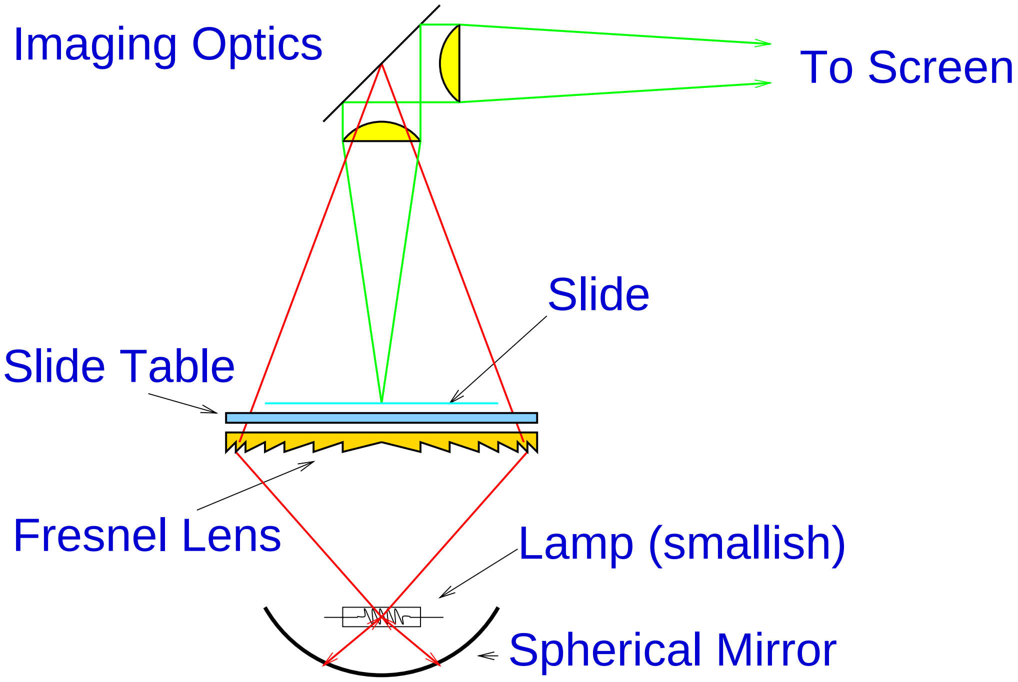
1. Molded glass light collection systems (in projectors).
2. Individual polishing or diamond machining. Both “one-off” manufacture, so expensive.
3. Used to deduce number of elements where weight or light efficency is essential.
4. Plastic molded surfaces. Plastic not ideal optical material.



Projector system has one aspherical surface to correct SA in the condensor.

Diffractive Optics:

1. Fresnel lens: Cheap and easy to make, but poor optical quality. Good to large light collection systems (OHP).
2. Holographic Optics: Monochromatic light only, difficult to mass produce. Specilist applications.



The OHP has a Fresnel (diffractive) condensor to collect light, but all other components are conventional glass spherical surfaces.

Optical Materials

Two basic optical measures of material performance:

$$n_d = \text{Refractive index at Sodium d-line}$$

and Abbe Number (also know as V-number), given by

$$V_d = \frac{n_d - 1}{n_f - n_c}$$

where

$$\begin{aligned} n_f &\rightarrow \text{Refractive index at Hydrogen f-line} \\ n_c &\rightarrow \text{Refractive index at Hydrogen c-line} \end{aligned}$$

where lines are at:

Na d-line → 587nm (Yellow)
H f-line → 486nm (Blue/green)
H c-line → 656nm (Red)

Available materials have:

$$\begin{aligned} n_d &= 1.4 \rightarrow 2.2 \\ V_d &= 80 \rightarrow 20 \end{aligned}$$

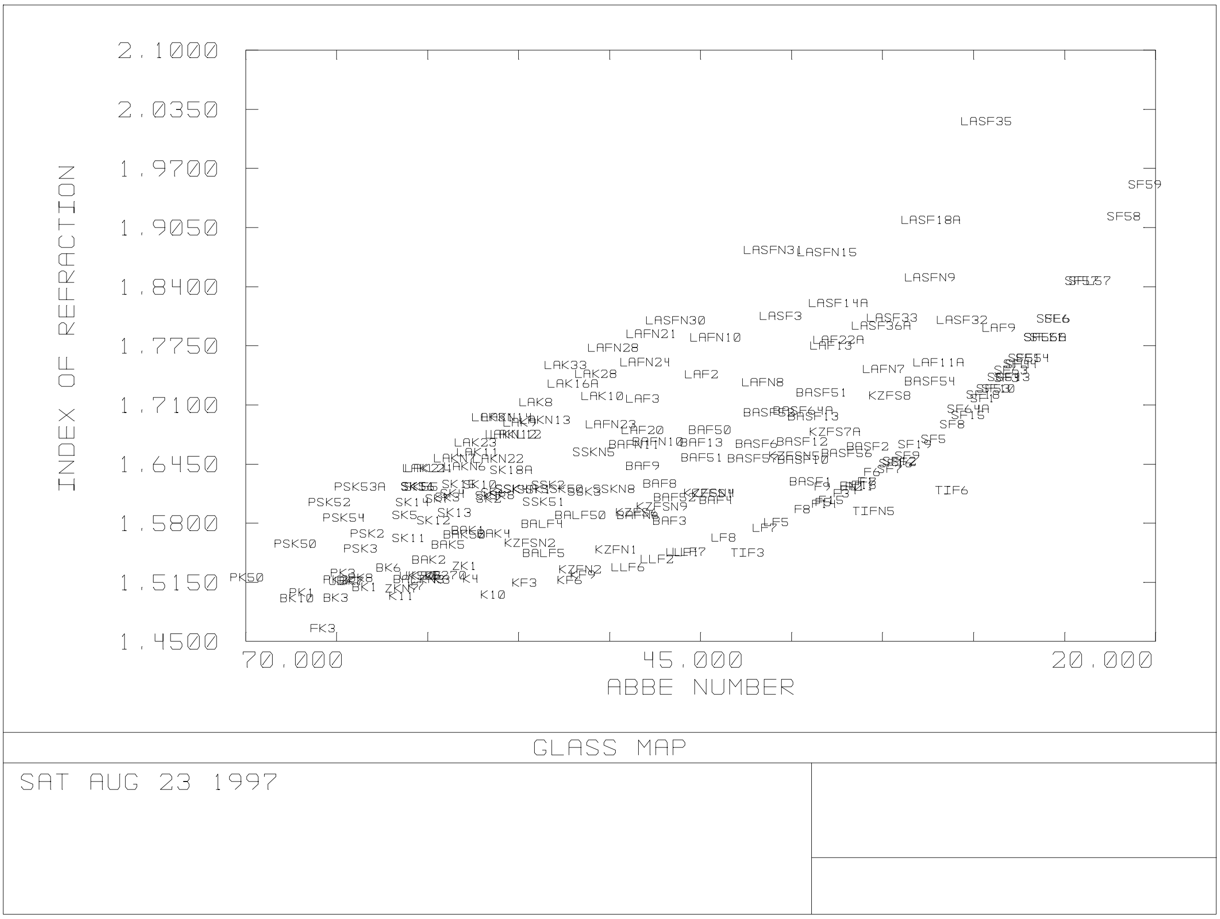
most common glass is borosilicate crown (Schotts BK7), with

$$n_d = 1.51680 \quad \& \quad V_d = 64.29$$

Many hundreds of optical glasses and plastics made with vast range of n_d and V_d values.

Glass Plot

Scatter plot of Refractive Index agaisnt Abbe Number



Note: Low Abbe Number means high dispersion, so most high refractive index glasses have high dispersion.

Glass Properties:

- Good optical quality, easy to polish spherical surfaces.
- Vast range of n and V values available.
- Thermally stable. Ignore expansion in almost all systems.
- Optical coatings easy.
- Many factory made components.

Problems:
range of problems selecting glass type, obvious ones are:

- Relatively easily broken.
- Heavy especially high n glasses that contain lead.
- Some high n glasses are “coloured”, or unstable.
- Factor of 1:300 (1:1000) in cost of raw material.
- Aspheric surface very difficult and expensive.
- Thickness of lens difficult to control in manufacture.

Almost all high quality optical systems use glass optics.

Optical Plastics

Plastic lenses look very attractive since:

- Easy to make in large numbers.
- Low cost of raw material.
- Aspheric surfaces easy, (once mold is made).
- Light and almost unbreakable.
- Lens thickness easy to control.
- Dye material to produce colour filters.

However the range of **problems** are rather sever, being

- Very limited range of n_d and V_d.
- Soft surface, and coatings difficult.
- High thermal expansion ($\times 8$ that of glass) and Refractive index is temperature dependant, ($> \times 100$ that of glass.)
- Expensive is small numbers due to cost of mold.
- Doublets not possible (thermal expansion problems.)

Useful for “low tech” optics only, spectical lenses, low-cost cameras, magnifiers.

New plastics with $n_d = 1.67$ and $V_d = 32$ just available in 1997.

Other Materials

Most glasses opaque outwith $350 \rightarrow 1300\,\mathrm{nm}$, so have to use other materials.

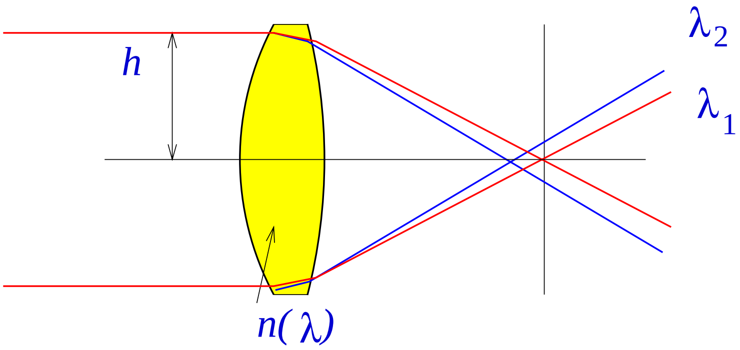
Ultraviolet: Fused quartz, calcium or lithium floride. Relatively few materials, expensive and difficult to shape. Also tend to be birefringent, and “cloudy”. Mainly used in spectrometer optics and UV microscope objectives.

Infrared: Limited range of glass transparent to $\approx 2\,\mu\mathrm{m}$, beyound that need to use Germanium or Silicon (both transparent $> 1.5\,\mu m$). Also Sodium Chloride (Salt) possible.

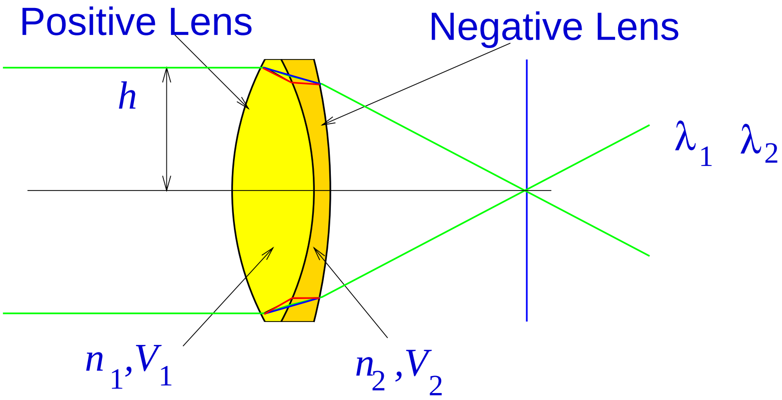
Thermal IR ($10\,\mu m$) of major importance. Mainly used diamond turned aspheric germanium lenses. Very high refractive index $n \approx 4$ and no good optical coatings so large reflection problems. Very expensive.

Chromatic Aberrations

For all glasses (and plastic) the refractive index n is a slow varying function of λ. So for a positive singlet the focal length depends on wavelength.



This is treated another aberration to be “cancelled”.



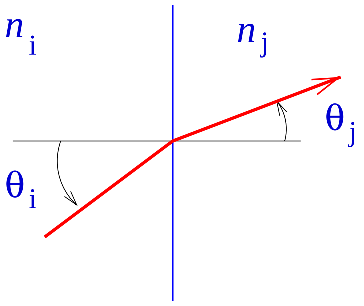
Combine a positive lens (with **low** dispersion), and a negative lens (with **high** dispersion) to give same focal length for same wavelengths.

(actually with a doublet on-axis cancel Spherical Aberration as well, so very useful lens.)

Ray Tracing

The concept of ray-tracing is fundamental to Lens, and System Design.

"Ray-Based" model, using effectively Snell's Law of



$$n_i \sin\theta_i = n_j \sin\theta_j$$

to trace rays through an optical system from object plane to image plane.

In vector form this becomes

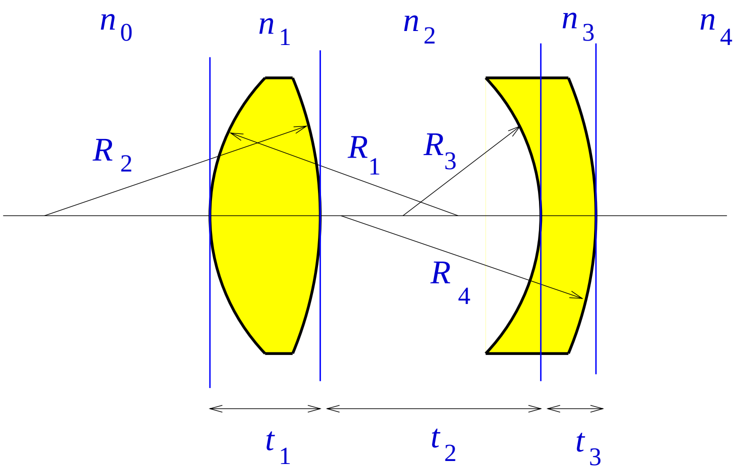
$$n_i(\vec{r}_i \wedge \vec{a}) = n_j(\vec{r}_j \wedge \vec{a})$$

where $\vec{r}_i$ is the ray direction and $\vec{a}$ is the surface normal.

Ray Model does not include any diffraction effects. These are usually added *after* the ray-trace by calculating the Wavefront Aberration, and hence the Effective Pupil Function.

Specification of Optical System.

Almost all optical system consists of “On-axis” spherical and plano surface lenses.



System is specified by a series of spherical surfaces, separations and refractive indices.

Surface Radi: Internally these are held as Curvatures,

$$C_i = \frac{1}{R_i}$$

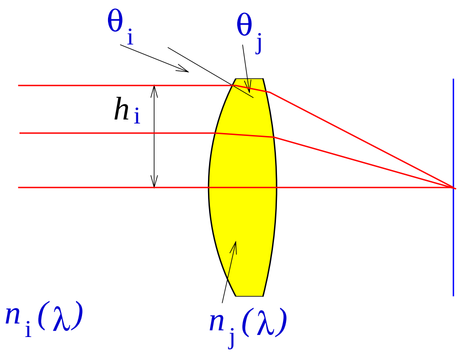
so that plano surfaces can be treated as Spherical Surfaces with curvature of Zero.

Separations: Distances between on-axis planes in contact with the surfaces. Zero is usually defined as centre of first surface.

Refractive Index: Depends on glass type and wavelength.

Trace Rays

Trace ray from surface to surface. At each surface.



Trace rays from "object" point to "image" by:

1. Calculate intersection point with surface from incident ray vector and lens data.
2. Calculate refractive index of interface for wavelength being traced.
3. Calculate surface normal to surface.
4. Calculate new ray direction by vector form of Snell's Law.
5. Calculate intersection with next surface, or image plane.

For infinite "objects" and/or "Images", define flat plane from which ray emanate or are analysed at.

If all surfaces are spherical then intersection points have analytic solutions.

Aspheric surfaces generally require iterative calculation on intersection point that seriously increase the calculation time.

Practical Ray Tracing

Ideal computer task, (actually second task ever applied to computers).

Analysis of Lenses and Systems: Assess performance, calculate PSF and OTF. From that obtain imaging properties (see previous lectures). Add polarisation, Gaussian beams etc.

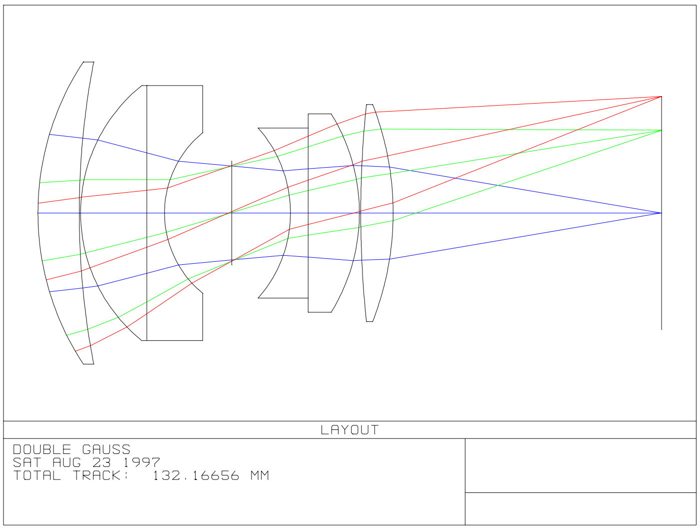
Design Lenses and Systems: Alter design (either manually or by iterative search), to optimise designs. (sound easy, but optimisation very difficult and needs skilled human intervention!).

Three “standard” software packages, (Code V, Zemax, Kidger Optics), all similar in function.

User to be considered “major computing task” (books before 1980s talk about “possibility of optimisations”).

Recently practical on “High performance” PCs. (calculation of OTF of 6 element on 128 × 128 grid takes 5 seconds on 200 MHz Pentium.)

Design of 6 elements Double Guass lens, $f = 100\,\mathrm{mm}$, $\mathrm{F}_{\mathrm{No}} = 3$ and half field angle of 14.8°. (Typical portrait lens on 35 mm camera)



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DOUBLE GAUSS
SAT AUG 23 1997
TOTAL TRACK:   132.16656 MM
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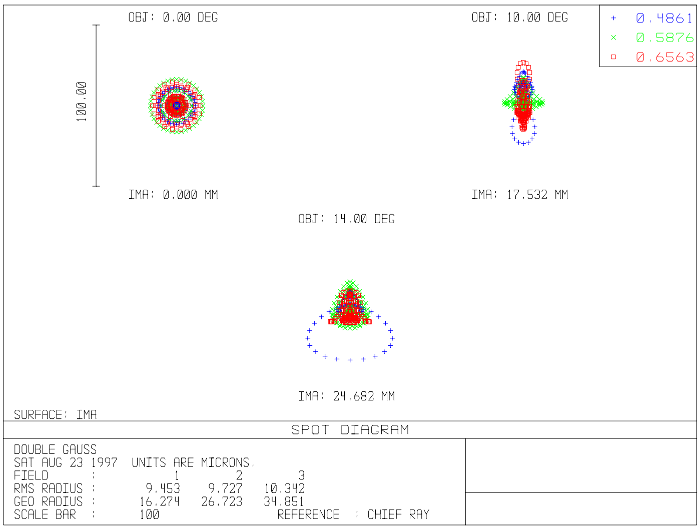
First analysis is to trace rays at produce “Spot Diagram” being scatter plot of where rays intersect image plane.



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DOUBLE GAUSS
SAT AUG 23 1997  UNITS ARE MICRONS.
FIELD       :          1         2         3
RMS RADIUS  :      9.453     9.727    10.342
GEO RADIUS  :     16.274    26.723    34.851
SCALE BAR   :      100              REFERENCE  : CHIEF RAY
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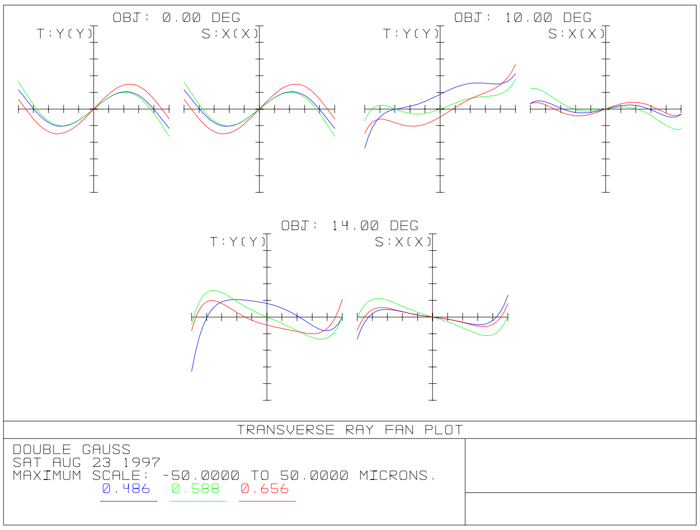
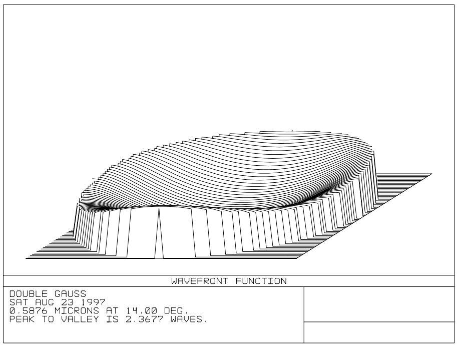
From traced rays plot rays aberrations, being deviation of rays from geometric locations.

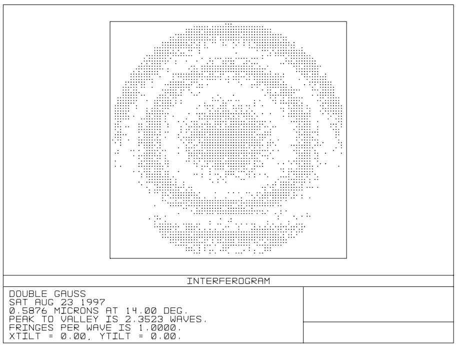


DOUBLE GAUSS
SAT AUG 23 1997
MAXIMUM SCALE: -50.0000 TO 50.0000 MICRONS.

Use these to project back to get the Wavefront Aberration $W(x,y)$,



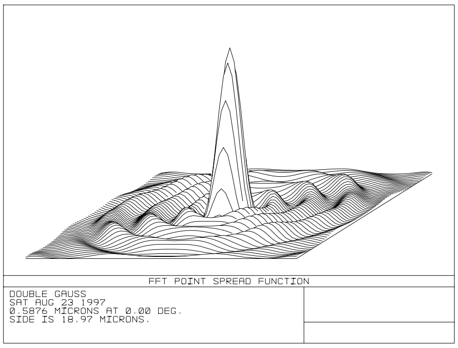
DOUBLE GAUSS
SAT AUG 23 1997
0.5876 MICRONS AT 14.00 DEG.
PEAK TO VALLEY IS 2.3677 WAVES.

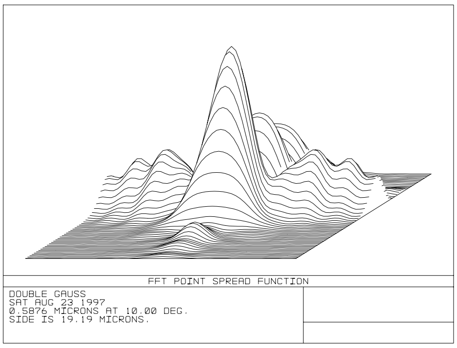


DOUBLE GAUSS
SAT AUG 23 1997
0.5876 MICRONS AT 14.00 DEG.
PEAK TO VALLEY IS 2.3523 WAVES.
FRINGES PER WAVE IS 1.0000.
XTILT = 0.00, YTILT = 0.00.

for one field angle. (these for angle of 14.8°).

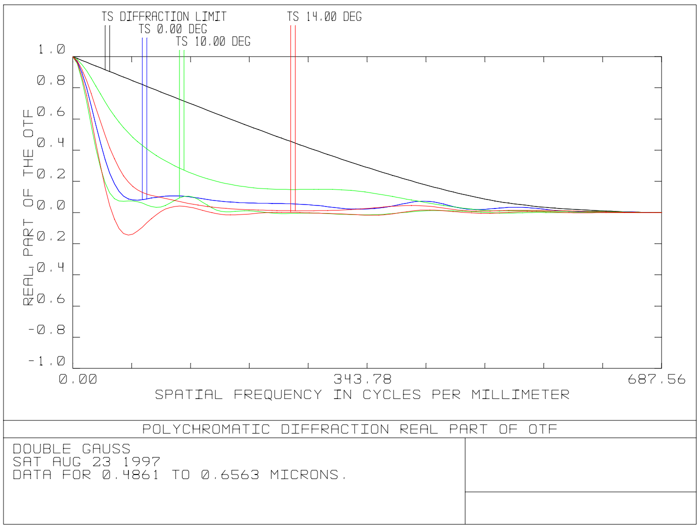
Then calculate the PSF for various field positions,





On-axis and 5° off-axis in this case.

And finally the OTF for the lens,



at a range of field angles.

So from ray-tracing you can do a full perfromance analysis of a design before any (expensive) production is undertaken.