Section 1
Part 3 – Design

Thanks to Robert Fischer, Rick Juergens, John Rogers, Jim Burge, Optical Research Associates and Photon Engineering for some of the illustrations and material in this section.

Design Process
Phases of the Design Process:

1) Conceptual Phase
   - Determine the basic system requirements based upon the customer needs
   - Identify design/system tradeoffs
   - Few hard specifications with many goals

2) Feasibility Phase
   - Identify the preferred configuration (# elements, etc.)
   - Rough estimate of the tolerance sensitivity
   - System layout
   - Mechanical/system interfaces

3) Final Phase
   - Match design to manufacturing tolerances
   - Final prescription
   - Mechanical/mounting design
   - Test plan

4) Fabrication Support
General Design Approach

Start with the requirements for the system.
- Without a complete set of requirements, the design may be wrong or useless.

Analyze the optical system requirements and define the first order design of the system.
- Identify subsystem modules.
- Define critical interfaces.

Use starting point resources (for example: patents, previous designs or published designs) to begin the design.
- Rather than reinventing the wheel, attack the real or new issues with the system.
- A majority of systems require incremental improvements rather than totally new approaches.

Use fundamental understanding of the methods of correcting axial and lateral color and third-order aberrations to identify promising solutions efficiently.

Classical solutions often offer good insights when attacking new problems (e.g., Double Gauss, Petzval, telephoto, etc.).

Design Resources

Books:
- Warren Smith: Modern Lens Design
- Milton Laikin: Lens Design
- Rudolf Kingslake: The History of the Photographic Lens

Patents:
- Lens View® - commercial program with over 10,000 patents
  However, avoid patent infringement issues.

Your personal experience and knowledge of design forms.
Constraints and Optical Design

Remember that you are not just designing a lens, but rather a portion of a system.

Maximize the fraction of the time dedicated to solving the actual problem.

The design challenge requires meeting all of the constraints of the system (performance, package, interfaces, cost, weight, schedule, temperature range, etc.).

The optical design may not be the defining driver for the overall system. The optical design may need to conform to the constraints introduced by other disciplines (mechanical, electrical, software, etc.).

Margins of error/tolerances must be realistic and shared between the disciplines.

Beware of CYA

The system should not be over-specified.

The customer must clearly communicate all of the rules that will shape the system design, and therefore the optical design.

On the other hand, successful system designs require that the customer be ready to compromise about the goals that are not critical or have fuzzy boundaries.

Applications of Optical Design

- Autofocus
- Binoculars
- Biocular displays
- Confocal microscopes
- Endoscopes
- Eyepieces
- High Energy Laser systems
- Flight simulators
- FLIR
- Fourier transform lenses
- Head-up/down displays
- Helmet-mounted displays
- Illumination (non-imaging)
- IR target scene generators
- Interferometers
- Laser range finders
- Laser scanners/Printers
- Laser target designators
- Machine vision
- Medical
- Microfilm reader/printers
- Microlithographic
- Microscope objectives
- Missile seekers
- Night vision systems
- Null lenses/CGHs
- Ophthalmic lenses
- Optical disk
- Optical pattern recognition
- Periscopes
- Photographic lenses
- Remote sensing
- Riflescopes
- Spectrographs
- Star trackers
- Telescopes
- Virtual reality displays
- Wavefront sensors
- X-ray phosphor lenses
- Zoom lenses

And many more…
System Specifications

The optical system must be designed to work with both the source or scene and the detector system. It is best that they be specified prior to the start of the optical design.

Source/Scene

- **Type**
  - Daylight (solar)
  - Artificial (synchrotron, xenon lamp, LED, blackbody)
  - Laser-based (excimer, UV, visible, NIR, IR)
  - Night lit (phosphor, intensifier)
  - Starlight
- **Wavelength**
  - Polychromatic/monochromatic
  - LWIR (8 - 15m)
  - MWIR (3 - 5.5m)
  - NIR (0.75 - 1, 1 - 3m)
  - Visible (0.4 - 0.75m)
  - UV (0.3 - 0.4m)
  - Deep UV (0.25 - 0.3, 0.1 - 0.25m)
  - Soft x-ray (to 0.01m)
- **Power (density)**
  - HEL (MW)
  - Photon counting
- **Coherence**
  - Coherent
  - Partially coherent
  - Incoherent
- **Polarization**
  - Yes/No
  - Birefringence
Optics

- **Size**
  - mm diameter
  - Many meter diameter
- **As-built performance**
  - High performance (< 0.01 waves RMS)
  - “Diffraction-limited” custom (< 0.1 waves RMS)
  - Detector limited (Nyquist)
  - Eye limited (accommodation factors)
- **Environment**
  - Underwater
  - Ground-based
  - Vacuum chamber
  - Airborne
  - Spaceborne
- **Operating temperature**
  - Cryogenic (4 - 77K)
  - Athermalized (-40 to +90°C)
  - Cooled HEL
  - High temperature (>100°C)
- **Material**
  - Glass
  - Plastic
  - Metal
  - Composite
  - Crystalline/polycrystalline
- **Manufacturing constraints:**
  - Off-the-shelf
  - Quantity (Prototype/Thousands)
  - Tolerance Constraints

Detectors

- **Type**
  - Eye (photopic/scotopic)
  - Film (AIM curve)
  - Photoresist
  - Photomultiplier
  - Silicon
  - IR focal plane
  - Linear array
  - CCD/CID array (pixel size)
- **Spectral coverage**
  - Visible
  - IR
  - UV
  - LWIR
  - Soft x-ray
- **Physical dimensions**
  - Pixel size
- **Limiting resolution**
  - 1 arc minute (eye)
  - 0.1 microns (x-ray lithography)
- **Sensitivity**
  - Light bucket
  - Photon counting
- **Response time**
  - Hours
  - Nanoseconds
Optical System Requirements

Performance:
• Provide imagery of sufficient quality to resolve specified minimum size objects over desired field of view.
• Image blur must be matched to detector size or resolution requirements.
• Clear aperture and transmittance must be sufficient for desired sensitivity.

Configuration selection:
• Design form must be capable of providing desired performance.
• Special requirements such as in scanning systems, cold stop efficiency in IR systems, etc. must be met.

Producibility considerations:
• Size / cost / weight / environmental effects

Optical System Specifications

Configuration (Source – Optics – Detector)
Focal Length
Field of View
Numerical aperture or F-number
Conjugates/Magnification (Finite/Infinite)
Object/Image Distance
Back Focal Distance
Spectral Range and Weights
Detector Parameters
Image Quality (MTF, RMS Wavefront, RMS spot size, Strehl, etc.)
Distortion
Vignetting /Relative illumination
Transmission (%)
Temperature Range and Thermal Gradients
Physical Constraints (Size, Element Size, Weight)
Windows and Filters
Ghost Image Requirements
Stray Light
Obstructions
Fabrication Constraints (Number of Elements, Surface Types, Tolerance Limits)
Assembly Compensators (Focus, Lateral Adjustment)
Cost Goals
Schedule Goals
Design Issues

What determines the Numerical Aperture (NA) or f/#?
- Resolution requirements
- Energy collection requirements
- Depth of focus

Design difficulty is a nonlinear function of the numerical aperture.
Costs increase significantly also.
Don’t specify more than is required.

Lagrange Invariant

The Lagrange Invariant is found by multiplying the image radius by the numerical aperture. This is a measure of the total amount of information passing through the system, and is a rough measure of the difficulty of the design task.

Field of View can be traded off with Aperture, but asking for more of both makes the problem more difficult.

The Lagrange invariant roughly determines the number of elements in a high-performance optical system.

The following plot shows contours of equal Lagrange Invariant and numbers of elements for state-of-the-art (ca. 1985) lenses.

Source: D. K. Towner
Image Quality and Manufacturing Tolerances

Design A is 23% better (RMS Wavefront Error) than Design B (before tolerances).
Design A is 821% worse than Design B with "standard" tolerances.

Specify the as-built performance not the design performance.

Optimization

The process of improving a design:
- to match the performance goal
- to meet system constraints
- to obtain a manufacturable system

Variables:
- Radii
- Thicknesses and Spacings
- Glass Types
- Number of Elements
- Aspheric Coefficients

Some of the variables allow for continuous change (radii and thicknesses), while others only change in discrete steps (glasses and number of elements).

Some parameters are easy to automatically optimize, others are not.
Merit Function

The Merit function is a single-number measure used to indicate quality.

Characteristics:
- Low is good.
- It should result in an acceptable solution.
- Easily and quickly computed.
- Self-consistent (two systems of similar quality should have similar merit functions).
- It should be controlled by the variables.

Form:
\[ \Phi = f_1^2 + f_2^2 + f_3^2 + f_4^2 + f_5^2 + \ldots \]

\[ f_i \rightarrow \text{Operands} \]

The goal is to pick the values of the variables to minimize the merit function.

The optimization is usually done in a least squares sense.

Operands

There are many, many options available within optical design software, and macros can be written to create more.

Paraxial Data
- Ray heights, slopes, focal length, f/#, etc.

Aberrations
- Amount of an individual aberration

System Data
- Edge thicknesses, center thicknesses, length, etc.
- Greater than, less than, equal.

Exact Ray Data
- Ray intercept errors (\( \varepsilon_X, \varepsilon_Y, \varepsilon_Z \))
- Wavefront errors, OPD

Combinations/Image Quality Metrics
- RMS spot size
- MTF
- Wavefront variance
- Others
Notes on Operands

There is a great deal of flexibility in selecting the operands.

Different terms can have different weightings.

Quality of the design will depend on the choice of the operands.

The rays used for the evaluation can also be selected (number, pupil positions, FOVs).

Terms for different wavelengths (and weightings) can be used.

There is no best merit function.

Glass types – instead of glass type, the system can be optimize on index and Abbe number. However, at some point real glasses must be selected.

Optimization Process

Pick a starting location or design (a set of variables).

Compute $\frac{\partial \Phi}{\partial v_i}$ for each variable (discrete derivatives).

Take a step in “variable space” to reduce the merit function. New values for the variables are obtained.

Re-compute the merit function $\Phi$ and repeat (iteration).

Stop when the merit function $\Phi$ does not change or is minimized.

The step size is decreased as the minimum is approached (damping).

In a real system there will be N variables. The merit function is differentiated with respect to each variable, and a “surface” gradient is created in N-space. A step is taken in N-space towards the minimum.

The optimization process is complicated by the fact that there is interplay between the variables. Not all the individual variable steps in N-space will be in the correct direction.
Local Minima

The optimum solution must be found in a multi-variable solution space with an almost infinite number of possible solutions.

The optimization can iterate to a local minimum of the merit function in solution space.

The designer must change the optimization to get out of these local minima and find a more optimum solution.

- Change weightings
- Different starting position
- Perturb the system

Oscillation and Stagnation

Oscillation – if the step size is too large, the solution can miss the minimum and bounce back and forth. Smaller step sizes or increased damping is required.

Stagnation – if the step size is too small or the gradient too low, it can take many iterations to reach the minimum
Global Optimization

Global optimization aims to solve the local minimum problem by exploring all of variable space to find the system configuration which has the best performance subject to any design constraints. The best performance is judged by the merit function.

- The system is perturbed to a new starting location and optimized from that point.
- A series of starting points is explored (random, semi-random, grid).
- The process is computationally intensive (often over-night).
- Discrete variables, such as the number of elements or glass type, can be changed with the different starting points.
- The initial starting location chosen by the designer should matter less.
- The design of the merit function is still critical, as are other system constraints.

Lens Design

- Optimization is not automatic.
- The starting point matters.
- The merit function defines the goal.
- In the end, only real glasses can be used.
- The system must be manufacturable (tolerances).

Merit Function:

- Build your own.
- Default (such as minimum RMS Spot Size).
- Modify the default.

What separates the professional lens designer from the amateur?
- Starting Point Choices
- Merit Function Design
- Tolerancing
- Experience!

There is no single “best” merit function. Two designers starting from the same specifications may produce two very different designs. This is one of the reasons lens design is often referred to as an art.
Lens Design Patents

![Graph showing cumulative US patents from 1860 to 2000. The x-axis represents the year, and the y-axis represents cumulative patents. The graph shows an exponential increase in patents over time.]

Lithography Systems

![Diagram illustrating the evolution of optical design for lithography from 1965 to 1993. Each year's design is depicted with specific parameters such as wavelength, element counts, and pixel densities.]

- Evolution of Optical Design for Lithography (1965-1993)
30 Element Design

Nikon Corporation

17 Element Lens
Corning-Tropel
About 700 mm long
All fused silica

Stop Shift for an Inward Bending Meniscus Lens

Smith – Modern Optical Engineering
Aberrations and Lens Bending – Stop at the Natural Stop Position

Tolerances

Tolerances indicate the precision to which elements can be fabricated and assembled.

The optical design must meet specification even in the presence of these variations.

The allowable errors are called tolerances:
- Machined Parts
- Dimensions of Optical Elements
- Optical Surfaces
- Material Properties
- Optical Assembly and Alignment

There are three basic level of tolerances (and associated costs):

Base/Commercial: Typical, no cost impact for reducing tolerances beyond this.

Precision: Requires special attention, but easily achievable in most shops.
May cost 25% more.

High Precision/Manufacturing Limit: Requires special equipment or personnel.
May cost 100% – 500% more.

Each fabrication shop will have their own set of tolerances based upon their capabilities.
Tolerance Forms

Symmetrical errors relating to fabrication, assembly, and materials
- Radius
- Power fit to test plate
- Thickness
- Airspace
- Refractive index

Asymmetrical errors in optical element
- Surface irregularity
- Inhomogeneity of refractive index
- Element wedge (total indicated runout)

Asymmetrical errors in assembly and alignment
- Element tilt, decenter or roll

Other
- Environmental effects
- Cosmetic effects (scratch, dig, bubbles)
- Dispersion of glass
- Combinations of above

Surface Figure and Irregularity

The surface characteristics are usually measured interferometrically:
- Fizeau interferometer – Using a test plate.
  - The specification is often given in fringes.
  - Phase Shifting Interferometers – Higher precision test especially for irregularity.
    - The specification is often given in microns or waves.

Separate tolerances are given for radius of curvature (or power) and irregularity.

The irregularity is found by removing the spherical component of the surface error.

The Fizeau fringes represent the departure of the test surface from the shape of the reference. Each fringe represents a departure of a half wavelength.

Once a manufacturer is selected, the design radii of curvatures should be varied to match existing test plates (if possible).

A typical surface specification on an optical surface measured with a test plate may be given as 3-1. Three rings (fringes) of power and one of irregularity.

For most diffraction limited systems, the RMS surface error is good figure of merit for irregularity.
Using Test Plates

When measuring power or irregularity, the bulls eye fringes should be centered.

Count the fringes in the long dimension and the short dimension:
- Power is the average of the two counts
- Irregularity is the difference of the two counts

Power fit = \(\frac{5 + 3}{2} = 4\) fringes
Irregularity = \(5 - 3 = 2\) fringes

Relating Sag and Radius of Curvature Tolerances

The “power” of a surface can be specified by either the Radius of Curvature of the Surface Sag.

\[
Sag = \frac{y^2}{2R}
\]

\[
Sag_{EDGE} = \frac{(D/2)^2}{2R} = \frac{D^2}{8R}
\]

\[
\Delta Sag_{EDGE} = \frac{D^3}{8R^2} \Delta R
\]
Element Wedge

Element wedge occurs when the mechanical axis of the element (defined by the edge of the lens) is displaced from the optical axis of the element (the line connecting the two centers of curvature).

Lens Wedge is the combination of a centered lens and a prism. Lens wedge deviates the light, which can cause aberrations in the system.

$$|\delta| = (n-1)\alpha$$

Wedge is optically equivalent to an element decenter.

Specifying Wedge

Wedge can be specified either by

- Beam deviation due to the prism.
- Edge thickness variation – measured total indicator runout (TIR).
Element Decenter and Tilt

Relate to element mounting.

Roll is a combination of Decenter and Tilt

Materials Tolerances

Refractive index value
Dispersion
Refractive index inhomogeneity
Sraie
Stress birefringence
Bubbles, inclusions
Cosmetic – Scratch and Dig

For best performance, obtain the actual melt data for the batches of glass that are being used. These values can be inserted into the optical design, and the system can be re-optimized based upon these values.
Scratch and Dig

The Scratch/Dig specification is what is usually considered a cosmetic standard for the presence of scratches and digs (pits) on the surface. From a functional perspective, it relates to scattered light and becomes especially important with coherent or laser light.

Scratch/Dig is specified by a number such as 60-40. The first digits relate to the brightness of the scratch, referenced to a master set of limits or reference samples at the U.S. Army Picatinny Arsenal. The second digits indicate the maximum diameter allowance for a dig measured in hundredths of a millimeter. There are additional requirements on the number of scratches and digs that may be present of the surface as defined by the standards: MIL-PRF-13830B or ANSI/OEOSC OP1.002.

The measurement is done visually by comparison to reference samples.

80-50   Commercial grade; non laser optics
60-40   Precision grade; low-power beams
40-20   Collimated laser beams; precision imaging optics close to a focal plane
20-10   Focused laser beams; high power
10-5    Ultra high power; intra-cavity optics

While the specification will vary with the form of the scratch, a #80 scratch is typically between 10 and 25 μm wide.

Mechanical Tolerances

Routine: ± 0.25 mm 0.010 inch
Precision: ± 0.025 mm 0.001 inch
High Precision: ± 0.002 mm 0.0001 inch

Grade
Drilling 10-13
Milling 10-13
Boring 8-13
Turning 7-13
Reaming 6-10
Diamond Boring 5-7
Diamond Turning 5-7
Surface Grinding 5-8
Lapping/Honing 4-5

ANSI B4.1 Standard Tolerances

![Graph of Tolerances](image-url)
### Optical Manufacturing Tolerances - Typical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base/Commercial</th>
<th>Precision</th>
<th>High Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Quality (index)</td>
<td>±0.001</td>
<td>±0.0005</td>
<td>Melt Data</td>
</tr>
<tr>
<td>Element Diameter (mm)</td>
<td>±0.00-0.10</td>
<td>±0.000-0.025</td>
<td>±0.000-0.010</td>
</tr>
<tr>
<td>Center Thickness (mm)</td>
<td>±0.200</td>
<td>±0.050</td>
<td>±0.010</td>
</tr>
<tr>
<td>Radius of Curvature (mm)</td>
<td>±0.5% + 5 frng</td>
<td>±0.1% + 3 frng</td>
<td>±0.025% or 1 frng</td>
</tr>
<tr>
<td>Surface Sag (mm)</td>
<td>±0.050</td>
<td>±0.025</td>
<td>±0.010</td>
</tr>
<tr>
<td>Power/Irregularity (fringes)</td>
<td>5-2</td>
<td>3-0.5</td>
<td>1-0.1</td>
</tr>
<tr>
<td>Surface Finish (Angstroms)</td>
<td>50</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Aspheric Profile (µm)</td>
<td>±5</td>
<td>±1</td>
<td>±0.25</td>
</tr>
<tr>
<td>Wedge TIR (mm)</td>
<td>0.050</td>
<td>0.010</td>
<td>0.002</td>
</tr>
<tr>
<td>Wedge Prism (arc min)</td>
<td>±3</td>
<td>±1</td>
<td>±0.1</td>
</tr>
<tr>
<td>Scratch-Dig</td>
<td>80/50</td>
<td>60/40</td>
<td>20/10</td>
</tr>
<tr>
<td>Bevels (Width @ 45°; mm)</td>
<td>1.0</td>
<td>0.1</td>
<td>None</td>
</tr>
<tr>
<td>Spacing (mm) Manual/CNC</td>
<td>±0.2 (±0.05 CNC)</td>
<td>±0.02 (±0.01 CNC)</td>
<td>±0.006 (±0.002 CNC)</td>
</tr>
<tr>
<td>Concentricity (mm)</td>
<td>±0.2</td>
<td>±0.10 → 0.025*</td>
<td>±0.025 → 0.005*</td>
</tr>
<tr>
<td>Coating</td>
<td>MgF₂ (R &lt; 1.5%)</td>
<td>BBAR (R &lt; 0.5%)†</td>
<td>Custom</td>
</tr>
</tbody>
</table>

†Broad Band Anti-Reflection  *without de-chucking

### Commercial Tolerances

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Commercial Quality</th>
<th>Precision Quality</th>
<th>Manufacturing Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Quality (n, k)</td>
<td>±0.001, ±0.05</td>
<td>±0.0005, ±0.05</td>
<td>Melt controlled</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>±0.00-0.10</td>
<td>±0.000-0.025</td>
<td>±0.000-0.010</td>
</tr>
<tr>
<td>Center Thickness (mm)</td>
<td>±0.150</td>
<td>±0.050</td>
<td>±0.005</td>
</tr>
<tr>
<td>Sag (mm)</td>
<td>±0.050</td>
<td>±0.025</td>
<td>±0.010</td>
</tr>
<tr>
<td>Clear Aperture</td>
<td>80%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Irregularity - Interferometer (fringes)</td>
<td>2 0.5 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irregularity - Profilometer (microns)</td>
<td>10 1 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wedge Lens (ETD, mm)</td>
<td>0.050</td>
<td>0.010</td>
<td>0.002</td>
</tr>
<tr>
<td>Wedge Prism (TIA, arc min)</td>
<td>±5</td>
<td>±1</td>
<td>±0.1</td>
</tr>
<tr>
<td>Bevels (face width @ 45°, mm)</td>
<td>&lt;1.0</td>
<td>&lt;0.5</td>
<td>No Bevel</td>
</tr>
<tr>
<td>Scratch - Dig (MIL-PRF-13830B)</td>
<td>80-50</td>
<td>60-40</td>
<td>5±2</td>
</tr>
<tr>
<td>Surface Roughness (Å rms)</td>
<td>2</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Air Coating (R&lt;∞, Å)</td>
<td>MgF₂, R &lt; 1.5%</td>
<td>BBAR, R &lt; 0.5%</td>
<td>Custom Design</td>
</tr>
</tbody>
</table>
Tolerancing

Tolerancing analyzes the system performance while taking into account the manufacturing and assembly limitations.

The goal:
- Predict the system performance for a given set of tolerances.
- Determine the required tolerances needed in order to achieve a certain level of system performance.
- Minimize manufacturing and assembly cost.

Will the system meet its optical requirements and be producible?

The error build up from the various manufacturing tolerances is statistical.

Tolerancing

Proper tolerancing is a balance between optical needs and mechanical capabilities.
- The optical designer and the mechanical designer must both be involved, preferably early in the design process (and preferably with the optical supplier also).

Preliminary tolerancing should be done early in the design process and tolerancing should continue throughout the design process.
- If the tolerances prove to be too tight, a different design form may be necessary, or specialized optical and mechanical fabrication and alignment techniques may be required.

This means that a mechanical engineer must be assigned to work with the optical designer from the start of the design process.

A manufacturing engineer may be involved as well to determine the assembly processes and identify the part of the performance budget used up by the assembly processes.
Optical vs. Mechanical Tolerances

Optical designers think in terms of simple tolerances which may end up as complex tolerances to the mechanical engineer.

For example, the optical designer may specify that the lens cannot laterally shift by more than a given amount:
- Mechanically, the lateral shift of a lens is a function of the lens outer diameter, the mount inner diameter, the mount's tolerances relative to other mechanical parts, the assembly and alignment technique, and a host of other mechanical tolerances that are often poorly understood by the optical engineer.

What may be simple to the optical designer, may end up as a complex tolerance allocation process by the mechanical engineer.

It is up to the optical and the mechanical engineers to ensure that the tolerance allocations on both the optical and mechanical parts meets the optical designer's tolerance specifications.

Optical tolerances generally have a graceful degradation rather than some mechanical tolerances which are simply pass/fail (e.g., it fits or it doesn’t).

Process of Optical Systems Tolerancing

1) Define quantitative figures of merit or performance criteria.
2) Estimate component tolerances
3) Select possible compensators
4) Define assembly/alignment procedure and estimate tolerances
5) Calculate sensitivities
6) Estimate performance
7) Adjust tolerances, balance cost and schedule with performance
8) Repeat
Performance Criteria

The first step is to identify the performance criteria that must be satisfied:
- MTF at particular spatial frequencies, RMS wavefront error, encircled energy, spot size, distortion, etc.
- Usually determined by the system engineers as part of the requirements flowdown.
- Keep the performance specification as simple as possible.

There must be sufficient margin between the design value of the performance criteria and the system performance requirement to allow for tolerances associated with fabrication and assembly.

Without a performance specification, there is no way to know if the lens design is good enough or if the tolerance limits are sufficient.

Compensators

Once the lens design form is identified and a preliminary mechanical design form is identified, potential compensators must be selected.

Compensators are the parameters which can be adjusted in the assembly and alignment process. Some typical compensators are:
- Defocus – almost always a compensator
- Spacers – compensates spherical aberration
- Decenter (push-around) – compensates coma

Without compensators (or with the wrong ones), the tolerances on the optics and on the mechanical parts will be unreasonably tight.

The allowed ranges of the compensator motions must be determined.

Usually, the optical designer will tell the mechanical designer what range is needed.

If needed range of motion is greater than what is mechanically feasible, other compensators must be found, the tolerances must be tightened, or the performance must be allowed to degrade.
Determine Sensitivities

The system performance change due to the perturbation of a parameter (radius, thickness, etc.) can be used to determine the tolerance sensitivity.

\[
\text{Sensitivity}_i = \frac{\partial \Phi}{\partial x_i} = \frac{\text{Change in Performance}}{\text{Change in Parameter}}
\]

\[
\Delta \Phi_i = \frac{\partial \Phi}{\partial x_i} \Delta x_i = (\text{Sensitivity}_i)(\text{Tolerance}_i)
\]

A different sensitivity is determined for each parameter.

\(\Delta \Phi_i\) is effect on system performance from a single parameter having an error equal to its tolerance.

When calculating the effect of each parameter, the value of any available compensators must be adjusted or optimized.

Estimate System Performance

By assuming that the effects of the individual tolerances are independent, the effect of the tolerances on the system performance can be estimated in a root-sum-squared RSS fashion.

\[
\Phi = \Phi_0 \pm \sqrt{\left(\Delta \Phi_1\right)^2 + \left(\Delta \Phi_2\right)^2 + \left(\Delta \Phi_3\right)^2 + ...}
\]

\[
\Phi = \Phi_0 \pm \sqrt{\left(\frac{\partial \Phi}{\partial x_1} \Delta x_1\right)^2 + \left(\frac{\partial \Phi}{\partial x_2} \Delta x_2\right)^2 + \left(\frac{\partial \Phi}{\partial x_3} \Delta x_3\right)^2 + ...}
\]

\(\Phi_0\) is the nominal system performance assuming no manufacturing or alignment errors.
The degradation of system performance due to a parameter tolerance can be seen, and the most significant contributors identified. For terms with small effects, loosen the tolerances, and for terms with big effects, the tolerances may need to be tightened.

Tolerances are adjusted to meet system performance requirements and to minimize cost.

### Spread sheet for Combining Tolerances

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tolerance</th>
<th>Sensitivity</th>
<th>Performance Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>$\Delta x_1$</td>
<td>$\frac{\partial \Phi}{\partial x_1}$</td>
<td>$\Delta \Phi_1 = \frac{\partial \Phi}{\partial x_1} \Delta x_1$</td>
</tr>
<tr>
<td>$x_2$</td>
<td>$\Delta x_2$</td>
<td>$\frac{\partial \Phi}{\partial x_2}$</td>
<td>$\Delta \Phi_2 = \frac{\partial \Phi}{\partial x_2} \Delta x_2$</td>
</tr>
<tr>
<td>$x_3$</td>
<td>$\Delta x_3$</td>
<td>$\frac{\partial \Phi}{\partial x_3}$</td>
<td>$\Delta \Phi_3 = \frac{\partial \Phi}{\partial x_3} \Delta x_3$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Total

RSS

Optical Design Codes

Much of the sensitivity analysis can be done entirely within the optical design code.

Tolerances can be specified, and the software will calculate sensitivities and derive an RSS system performance.

As an alternative to the RSS approach, optical design codes also include a useful Monte Carlo type tolerance analysis. This method creates numerous simulations of your system with all of the degrees of freedom perturbed by random amounts. This approach will take into account interactions between tolerances.
Confidence Levels

Assume Gaussian statistics:
   It is easy and on the average, it is correct.
   Any one system will not follow these statistics exactly.

Use tolerance analysis to establish confidence levels:

<table>
<thead>
<tr>
<th>Range</th>
<th>± σ</th>
<th>±2 σ</th>
<th>±3 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence level</td>
<td>68%</td>
<td>95%</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

Common assumptions for tolerancing:
- All error terms are handled so that the tolerance represents ±2σ or 95% confidence.
- The RSS of all of these terms can then be interpreted as ±2σ or 95% confidence.
- This method provides 95% yield (5% rejection).

RSS Example

Consider the height of a stack of 100 coins.

The thickness of each coin is 1 mm ± 0.05 mm.

The maximum range of stack heights is 95 mm to 105 mm (100 mm ± 5 mm), however this range is almost impossible to obtain. If the thickness errors are random, some coins will be too thick and some too thin.

Since the stack height will change by the error of each individual coin, the sensitivity is unity:

\[
\text{Sensitivity}_i = \frac{\partial \Phi}{\partial x_i} = 1 \quad \Delta \Phi_i = \Delta x_i = 0.05\text{mm}
\]

\[
\Phi = Nt = N(1\text{mm})
\]

\[
\Phi = \Phi_0 \pm \sqrt{(\Delta \Phi_1)^2 + (\Delta \Phi_2)^2 + (\Delta \Phi_3)^2 + \ldots} = \Phi_0 \pm \sqrt{N(\Delta \Phi)}
\]

\[
\Phi = 100\text{mm} \pm \sqrt{N(\Delta \Phi)} = 100\text{mm} \pm 0.5\text{mm}
\]

This is the 95% confidence level for the variation of stack height.
Sensitivity Analysis Example

Example: 2 inch diameter, f/2 silicon-germanium doublet

<table>
<thead>
<tr>
<th>Surf</th>
<th>RDY</th>
<th>THI</th>
<th>GLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.65</td>
<td>0.25</td>
<td>Si</td>
</tr>
<tr>
<td>2</td>
<td>10.78</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14.30</td>
<td>0.15</td>
<td>Ge</td>
</tr>
<tr>
<td>4</td>
<td>6.80</td>
<td>(3.54)</td>
<td></td>
</tr>
</tbody>
</table>

Analyze the MTF at 50 lp/mm

The sensitivity analysis should also include the amount of compensation that is required for each tolerance parameter.
The Tolerance Process

After performing a sensitivity analysis, the full tolerance process is performed.

In general, the idea is that each tolerance pulls its own weight.

This means that the change in the performance measure is roughly the same for each of the tolerances:
- For example, the loss in MTF is 1% for each tolerance.
- Some tolerances may be loose while others may be tight.

This will not always be possible:
- Some parameters may be very tolerant of change
  - Do not let the tolerances get too loose (e.g., lens CT = 0.5 ± 0.1 mm)
- Some parameters may be very sensitive
  - Do not let the tolerances get too tight (e.g., lens CT = 0.5 ± 0.0001 mm)

Do not select too many compensators:
- They can fight each other - be sure they are independent!
- Ideally, compensators are orthogonal (e.g., do not use multiple focus compensators).
- Only select compensators that move things, such as focus or axial motion of a lens.
Iterating the Tolerance Process

The tolerance run will make a statistical prediction for performance and yield.

If the system goals for performance and cost are not met, changes need to be made:
- Tighten selected tolerances
- Change or add compensators

In some cases (with luck), the tolerance run will show performance margin. In this case, some tolerances can be loosened or some compensators can be deleted to reduce manufacturing costs.

In some cases, the performance yield is sufficient, but the compensator motion is excessive:
- Tolerances need to be tightened until the compensator motion is within bounds.
- Select other compensators.

Symmetric Tolerances

Airspace

Focus Compensation
Airspace – 1 mm Error

Before

After

- Spherical aberration
- Focal length (magnification) error

Asymmetric Tolerances – Wedge, Tilt, Decenter

Errors which break symmetry affect:
- Aberrations (Blur size)
- Boresight Error
Asymmetric Tolerance Example - Decenter

Decenter – 25 micron Decenter
Asymmetric Tolerance Example - Tilt

Tilt – 0.25 degree

Before

After
Encircled Energy

Tolerances make a large change to the 86% encircled energy diameter

<table>
<thead>
<tr>
<th>f/8 laser focus</th>
<th>(0.000,0.000) DEGREES</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-designed</td>
<td>As-built</td>
</tr>
</tbody>
</table>

Two Classes of Tolerances

Tolerances on a single optical component
- These tolerances are found on the drawing for the element:
  - Radii and surface figure (power, irregularity)
  - Special surface parameters (e.g., aspheric parameters)
  - Thickness (at vertex and of sag flats)
  - Index and dispersion
  - Wedge

Tolerances on assembling optical components into a system
- These tolerances are found on assembly drawings or on the mechanical parts:
  - Axial displacements of an element or of a group
  - Tilt and displacement of a single element
  - Tilt and displacement of elements as a group
Element Mounting and Lens Assembly Methods

Low precision: lenses dropped in a barrel
- Diameter tolerance: fit issues/decenter errors
- Centration tolerance: element wedge/tilt
- Bevel tolerance: element spacing error and element tilt error

High precision: lenses in cells bolted together
- Precision cementing or flexure design

Tolerancing Tools
The main tolerancing tool in lens design programs (such as CODE V) compute the effects of tolerances on diffraction MTF or RMS wavefront error.
- These metrics allow tolerancing methods based on wavefront differentials.
- Computing the effects of tolerances on these performance metrics can be done very rapidly.

If you want to use a different performance metric, such as energy on detector, then you must use a different tool, such as Monte Carlo tolerancing.
- This method models many perturbed systems, computes the performance of each, and develops a statistical summary of possible performance levels.
- Can be a long process (many hours or even overnight runs).
Monte Carlo Tolerancing

1. Restore Lens
2. Perturb Lens
3. Optimize Lens
4. Evaluate performance metric(s)
5. Have enough samples?
   - Yes: Perform statistical analyses
   - No: Random variations of all parameters with tolerances: Radii of curvature, Thicknesses, Spacings, Refractive indices, etc.

These steps usually require user-written macros.

Case #1
- 0.5 mm CT error
- 10 fringe radius error
- Allow refocus

Case #2
- 0.1 mm CT error
- 3 fringe radius error
- Allow refocus
Tolerancing Tips

It is very likely that it will take you longer to tolerance the lens than it took to design it.
- Allow for significant time and effort in the tolerancing phase of the job.

Work closely with the mechanical engineer to be sure that you are modeling the system as it will be built:
- Model the tolerances as they appear on the drawings.
- It makes it easier to correlate the results to the source of the problems.
- Use the compensators agreed upon with the mechanical engineers.

Work closely with the possible lens suppliers to be sure the tolerances you are using are feasible and practical (and cost-effective).

The "Knee" of the Curve

Many applications behave in the manner indicated in the following graph:

The cost is driven by specifications, constraints and tight tolerances.

In such cases, the appropriate action is to search for the point where things begin getting difficult rapidly, and readjust the goals accordingly.
Non-Sequential Raytracing

Sequential Raytracing traces rays through a system in optical order according to the prescription. At each surface, reflection or refraction occurs. It is used to design, optimize and tolerance systems of lenses and mirrors.

Non-Sequential Raytracing use a three-dimensional model of the system. Rays are launched from a source and they propagate until they hit something. At the surface, the ray can be partially transmitted, partially reflected and/or scattered according to defined surface properties. The surface can be a lens mount as well as a lens element. The input ray is split into a number of rays, and these “daughter” rays each propagate until the another surface is encountered. A ray can encounter surfaces in any order and any number of times.

Non-Sequential Raytracing follows the physical trajectories of rays as they interact with the optical system. The rays are not constrained by a predetermined order of surfaces.

Important applications of non-sequential raytracing include:

- Illumination design
- Projectors
- Automotive and architectural
- Backlighting
- Stray light analysis
- Ghost images/Lens flare
- Source modeling

Weightings can be applied to account for the percentage of light associated with each resulting ray.
Source Modeling

CFL

LED Collimator

Optical Research Associates

Optical Research Associates

All Directions

Rays directed only in the direction/area of interest.
Example – Automotive Reflector

Scene Simulation

Roadscene with Headlights and LED Streetlights
Example – Source, Reflector and Integrating Bar

Examples

Faceted Reflectors

Light Pipe
Stray Light Analysis

By adding realistic surface properties, non-sequential raytracing can be used to analyze the stray light properties of an optical system:
- Reflectivity
- Transmission
- Absorption
- Scattering Distributions

The analysis can also determine if there are any unintended optical pathways through the system.

The Bidirectional Scatter Distribution Function BSDF is used to characterize the scattering at the surface.

The BSDF is comprised of two components:
- BRDF: Bidirectional Reflectance Distribution Function
- BTDF: Bidirectional Transmission Distribution Function

Surface Scatter Models

Rays spread after scattering by reflection or transmission.

The ray propagation direction can be Transmitted (forward scatter), Reflected (back scatter) or both.

The BSDF (or BRDF and BTDF) measure the scattering distribution:
- The scattering function varies with both the angle of incidence and the angle of reflection/transmission.
- Most scattering distributions are centered about the specular direction.

\[ BRDF(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL_e(\theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)} \]

Lambertian:

\[ BRDF_{L} = \frac{\rho}{\pi} \equiv \text{Constant} \]

\[ \rho = \text{Reflectivity} \]
Scattering Functions

$\theta_i = 0^\circ$

$\theta_i = 20^\circ$

$\theta_i = 40^\circ$

$\theta_i = 50^\circ$

$\theta_i = 60^\circ$

Libraries of BSDFs are available in the non-sequential raytrace programs. Care must be taken to use a BSDF that matches the actual surface. Best results may require measurement of BSDF.
Cassegrain Telescope Example

Detector Array
Focal Plane

Optical Research Associates

Catadioptric Lens System – Stray Light and Baffles

Scattering from edges of lenses and mounts

Addition of a baffle at the primary mirror.

Addition of a second baffle.

Ghost Images and Lens Flare

Unlike the degradation of images from scattered light, ghost images are unintended images caused by specular Fresnel reflections from refracting surfaces in the optical system.

To form a ghost image, the light must reflect off an even number of surfaces, so that there are two-reflection ghosts, four-reflection ghosts, etc.

Ghosts are usually only formed by bright sources within or just outside the field of view. If the surface reflectivity is $\rho$, then the ghost will have an relative irradiance of $\rho^N$ where $N$ is the number of reflections. For example, a two-reflection ghost from uncoated glass will have an irradiance about 0.16% of the direct image of the source producing the ghost. For AR-coated glass with $\rho = 1\%$, the relative irradiance will be 0.01%. In addition to overall transmission, the minimization of ghosts is a good reason for high quality AR coatings on camera lenses.

Lens flare is the term applied to the combined effects of scattered light and ghost images.
Ghost Images and Lens Flare

Since most ghost images are "out of focus," the ghosts often appear as the aperture shape of the stop in the optical system. It is sometimes possible to determine the number of blades in the iris diaphragm by examining the shape of the ghost images. It is possible for the ghost to be an in-focus replica of the scene.

There are several effects on an image by scattered light:
- a halo around bright object points.
- overall contrast reduction or a contrast variation.
- streaks caused by scattering from a mount or lens edge.
- light that misses the optical elements (reflective systems).

The axial location of the ghost will depend on the imaging properties of the surface curvatures involved in producing the ghost image. Remember that the surfaces must be treated as reflecting surfaces for the analysis.

All reflective systems cannot produce ghost images.

An interesting effect can occur in digital imaging systems. Light can reflect off the sensor then reflect off an optical surface to produce a ghost. Since the pixels on the sensor look like a diffraction grating, rainbow ghosts can be produced. This type of ghost cannot be seen through an optical viewfinder.

Ghost Image Analysis

http://www.optenso.com/optix/ex_ghost.html
The top system is a doublet with perfect anti-reflection coatings. The bottom system is a doublet with uncoated glass.

Double Gauss lens with uncoated surfaces:

Note the difference in the irradiance level of the two plots.
Veiling Glare

Veiling glare is a measure of the image contrast reduction due to scattering in the optical system.

Sources for this scattered light include:
- Reflections between lens surfaces.
- Surface imperfections (dirt, surface finish, scratches, poor AR coatings).
- Bubbles and striae.
- Edges of lenses, lens mounts and barrels.
- Surfaces of diaphragm or shutter blades.
- Reflections from the detector or film.
- Fluorescence of the glass or optical adhesives.

Veiling glare is a system property, and it should be measured for the complete system. The veiling glare of the lens can be different from the veiling glare of the entire camera.

The usual way to measure veiling glare is to image a black area on a white background. Light will scatter from the white region into the black area, and the decrease in contrast is measured.

Veiling Glare Targets

\[ \text{Veiling Glare} = \frac{E_B}{E_W} \]

Alternate Target:
Target Construction

The black area of the test target for veiling glare should be as black as possible. Even black paints and coatings can have a reflectance of 0.5-1%.

Truer blacks can be obtained by using a cavity with multiple reflections – a light trap.

![Side Views](image)

The interior of the cavities should be coated with gloss black paint. This provides absorption without scattering (as would be obtained with flat black).

For information: Black velvet is a very good black covering.

Film Resolution

Due to the grain size of film, there is an MTF associated with films.

![Figure 11.02 Modulation transfer function of several photographic emulsions.](image)

A reasonable guide for MTF of a 35 mm format camera lens is the 30-50 rule:
- 50% at 30 lp/mm and 30% at 50 lp/mm.

For excellent performance of a camera lens, use 50% at 50 lp/mm.

Another criterion for 35 mm camera lenses is 20% at 30 lp/mm over 90% of the field (at full aperture).

As a rough guide for the resolution required in a negative, use 200 lines divided by the square root of the long dimension in mm.