Introductory Optomechanical Engineering
OPTI 421/521 University of Arizona

Specifying Optical Components

- Lenses, Mirrors, Prisms,…
- Must include tolerances
  - Allowable errors in radius, thickness, refractive index
- Must consider
  - Surface defects
  - Material defects
  - Mounting features

We only touch on this topic here. If you want to design real systems, you should take

OPTI415/515 *Optical Specification, Fabrication, and Testing*

I provide some reference here. I will go through it very quickly, assuming that you will either get this in 415/515 or that you will study this on your own. This is important. Don't leave school without it.

Dimensional tolerances for lenses

Diameter tolerance of 25 ± 0.1 mm means that the lens must have diameter between 24.9 and 25.1 mm

Lens thickness is almost always defined as the center thickness

Typical tolerances for small (10 - 50 mm) optics:

Diameter +0/-0.1 mm

Thickness ± 0.2 mm

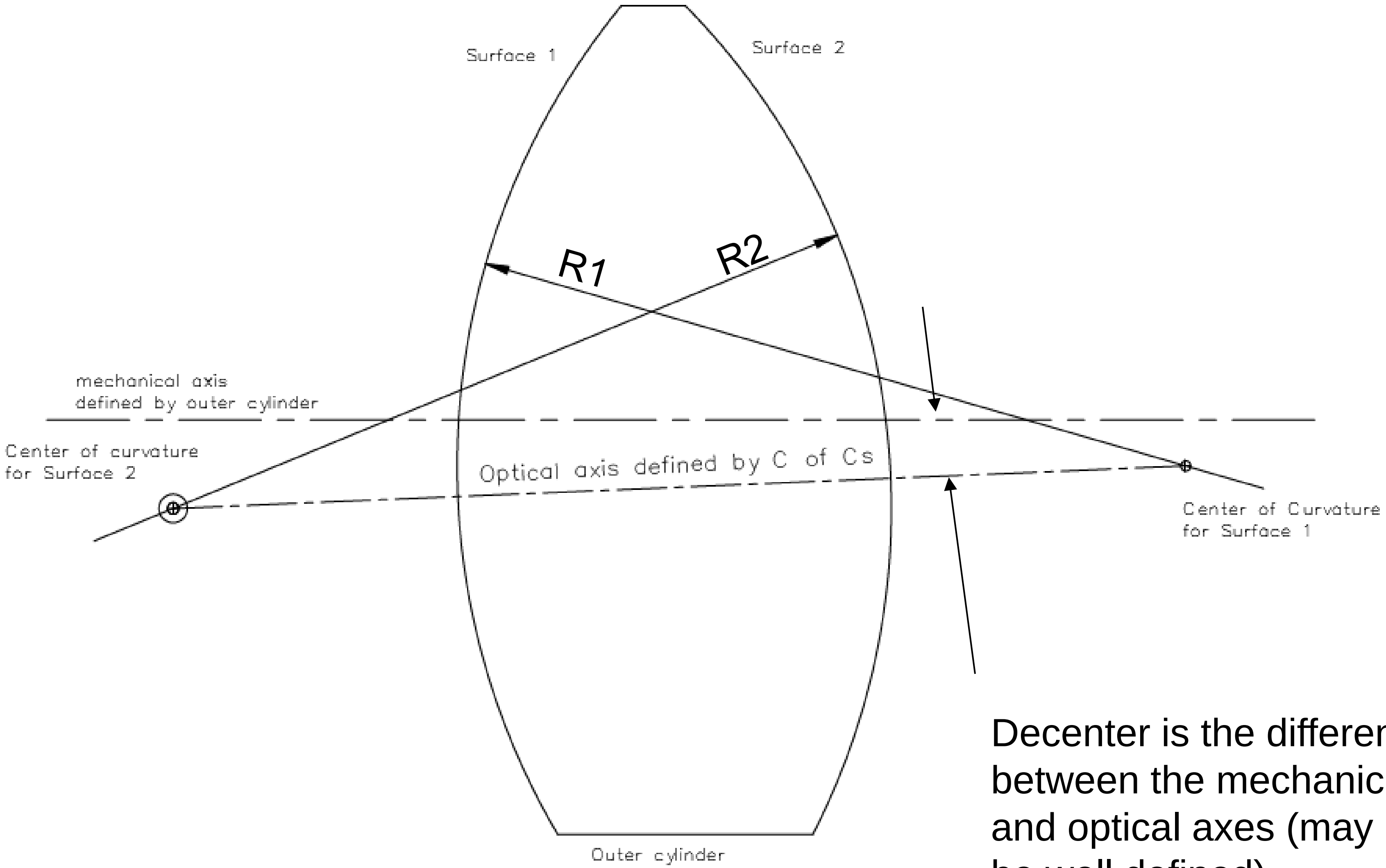
Clear aperture is defined as the area of the surface that must meet the specifications. For small optics, this is usually 90% of the diameter.

Understanding wedge in a lens

- "wedge" in a lens refers to an asymmetry between
  - The "mechanical axis", defined by the outer edge.
  - And the "optical axis" defined by the optical surfaces

Lens wedge deviates the light, which can cause aberrations in the system

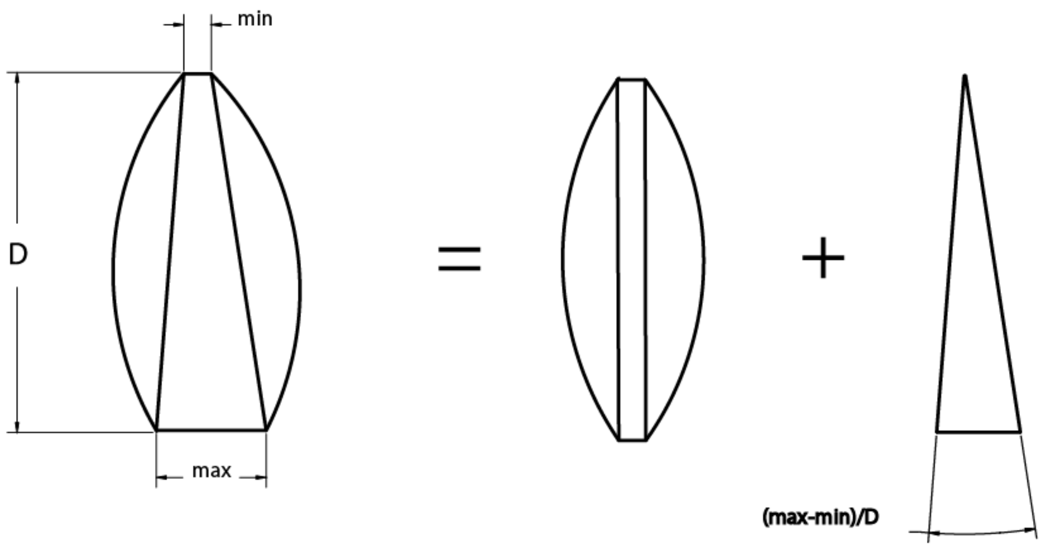
Optical vs. Mechanical Axis



Decenter is the difference between the mechanical and optical axes (may not be well defined)

Wedge in a lens

- The optical axis of a lens defined by line connecting centers of curvature of the optical surfaces
- The mechanical axis defined by outer edge, used for mounting.
- Wedge angle α = Edge Thickness Difference (ETD)/Diameter
- Deviation $\delta = \alpha(n-1)$ defined by light going through the lens
- Lenses are typically made by polishing both surfaces, then edging. The lens is held on a good chuck and the optical axis is aligned to the axis of rotation. Then a grinding wheel cuts the outer edge.
- The wedge specification dictates the required quality of the equipment and the level of alignment required on the edging spindle. Typical tolerances are
  - 5 arcmin is easy without any special effort
  - 1 arcmin is readily achievable
  - 15 arcsec requires very special care



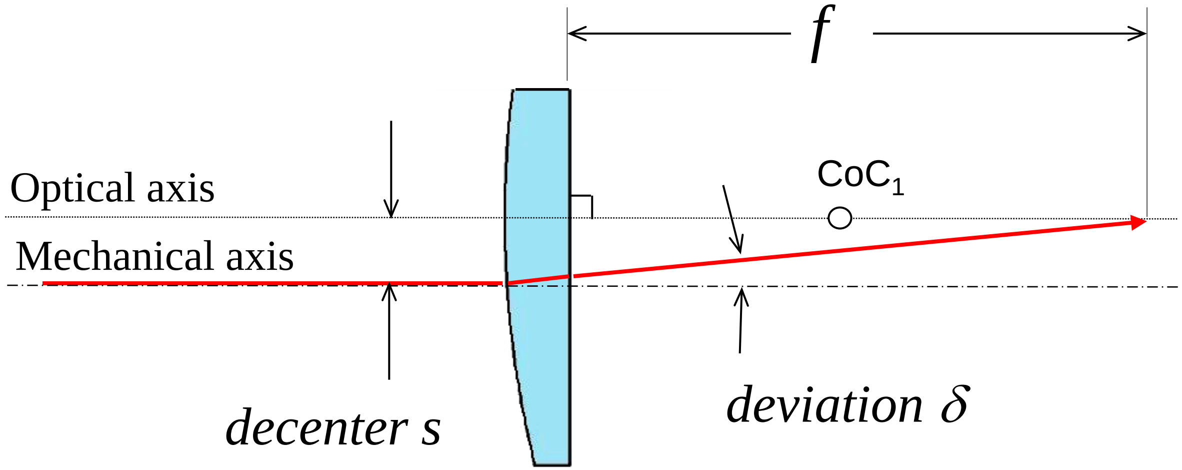
$$ETD = max - min$$

$$\alpha = ETD / D$$

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

Lens element centration

- Lens wedge can also be describe as centration. This is defined as the difference between the mechanical and optical axes.



$$\delta = \frac{s}{f} \qquad \alpha = \frac{ETD}{D}$$

$$\text{Wedge } \alpha = \frac{\delta}{n-1} = \frac{s}{f\,(n-1)} \qquad s = \frac{ETD}{D} f\,(n-1)$$

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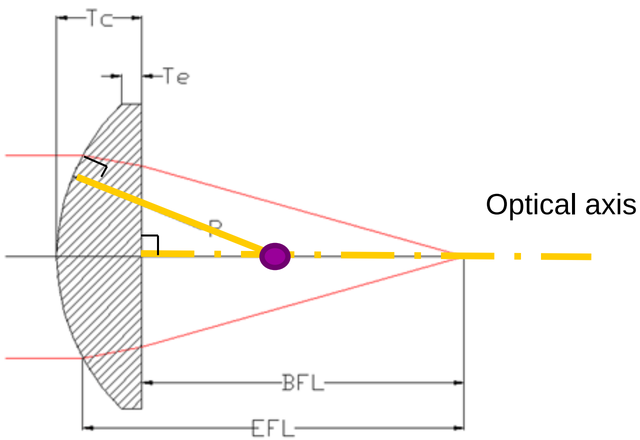
Lens axis

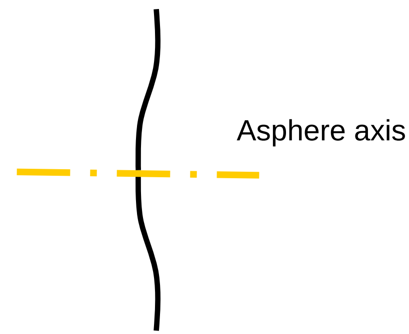
Plano-concave or plano convex

S1 center of curvature + surface normal



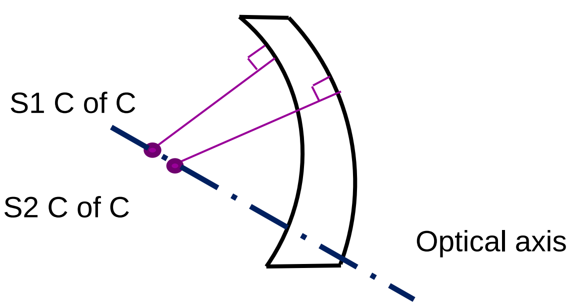
Aspheric surface

Unique axis is defined



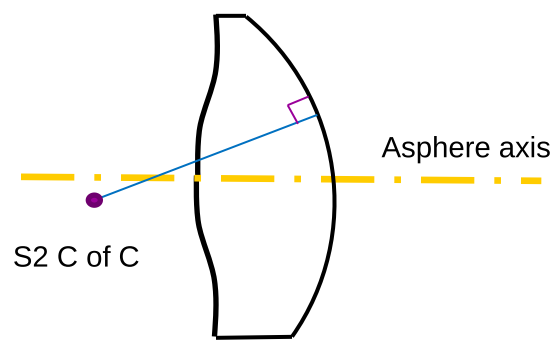
Near concentric surfaces

Optical axis can have large offset



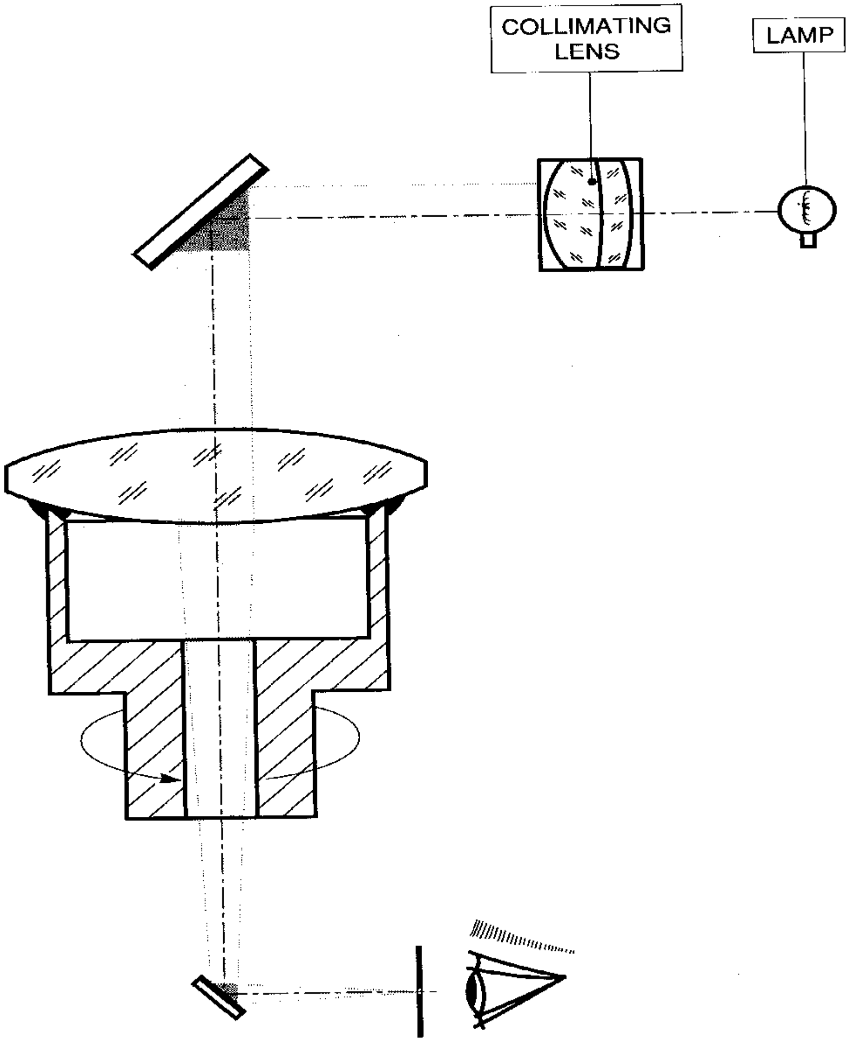
Lens with aspheric surface

True optical axis is ambiguous



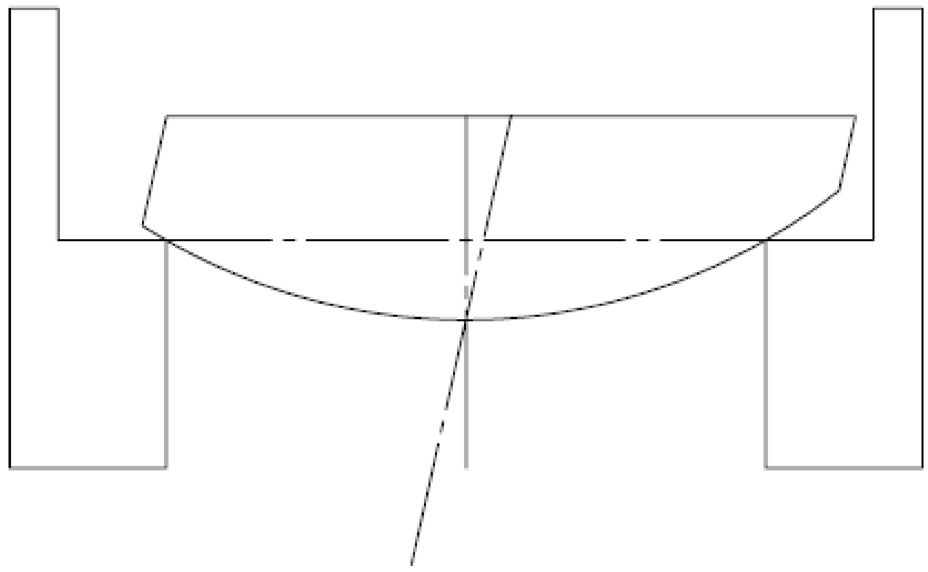
Centering a lens

1. Use optical measurement



Lens mounts: align the *optical* surfaces

Mechanical surface can be in the wrong place with no negative consequences

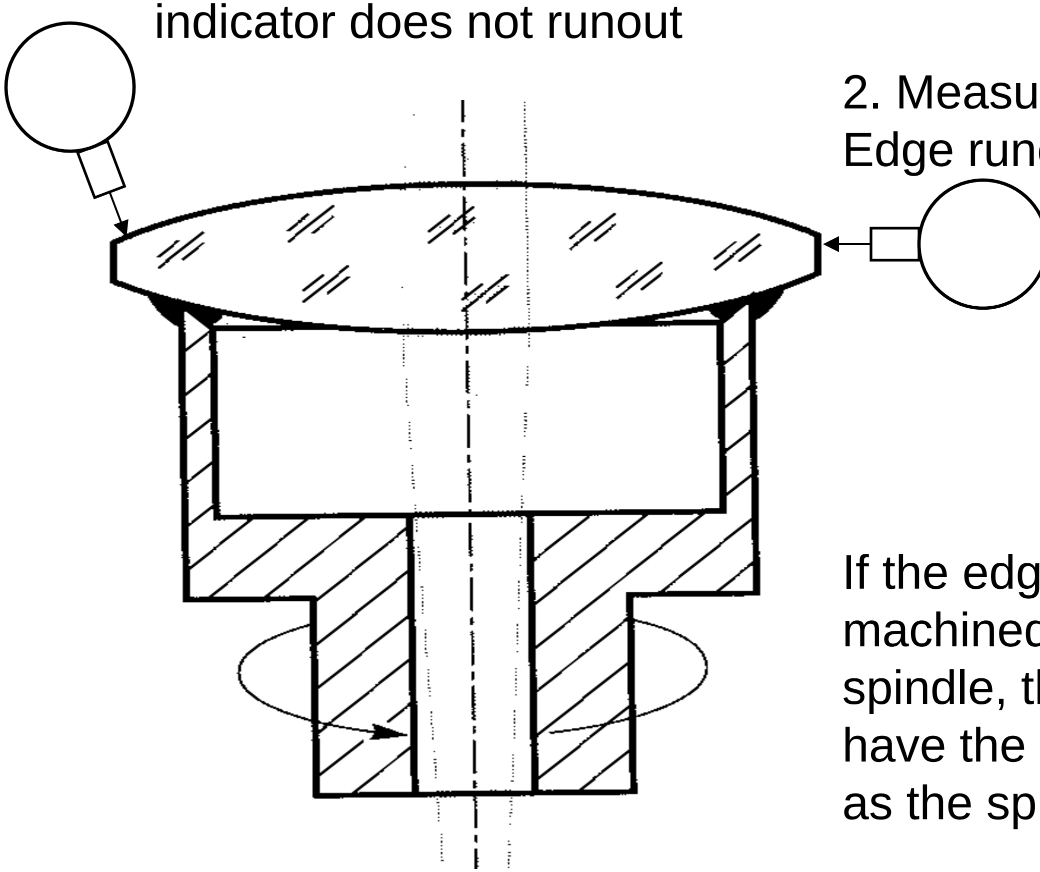


Centering a lens

- Use mechanical measurement

1. Move lens until dial indicator does not runout

2. Measure Edge runout



If the edge is machined on this spindle, then it will have the same axis as the spindle.

Specification of lens wedge using ISO10110

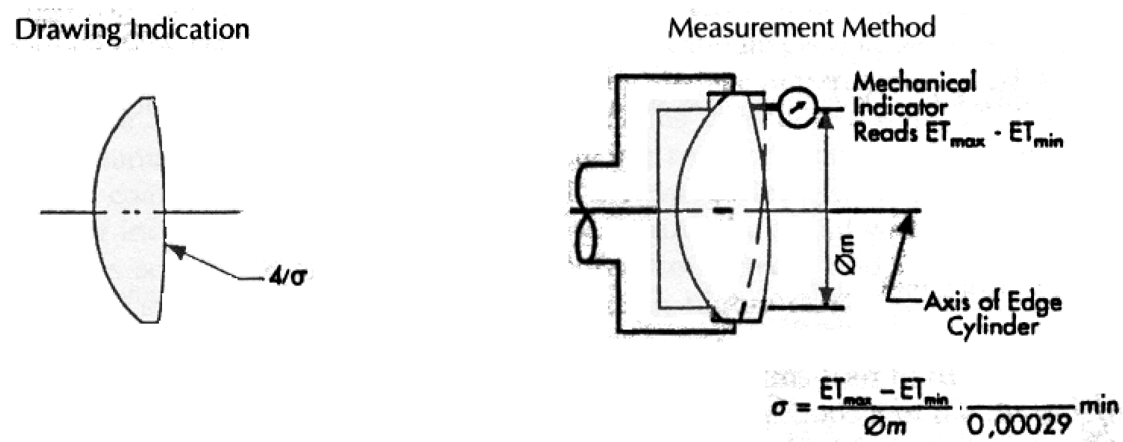


FIG. 6.4. Measurement of surface tilt using mechanical metrology.

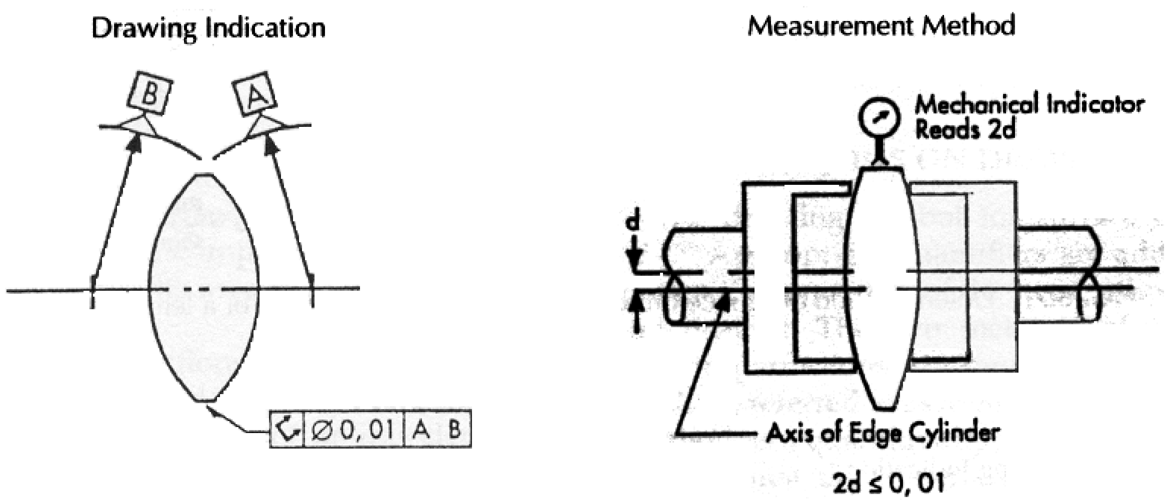
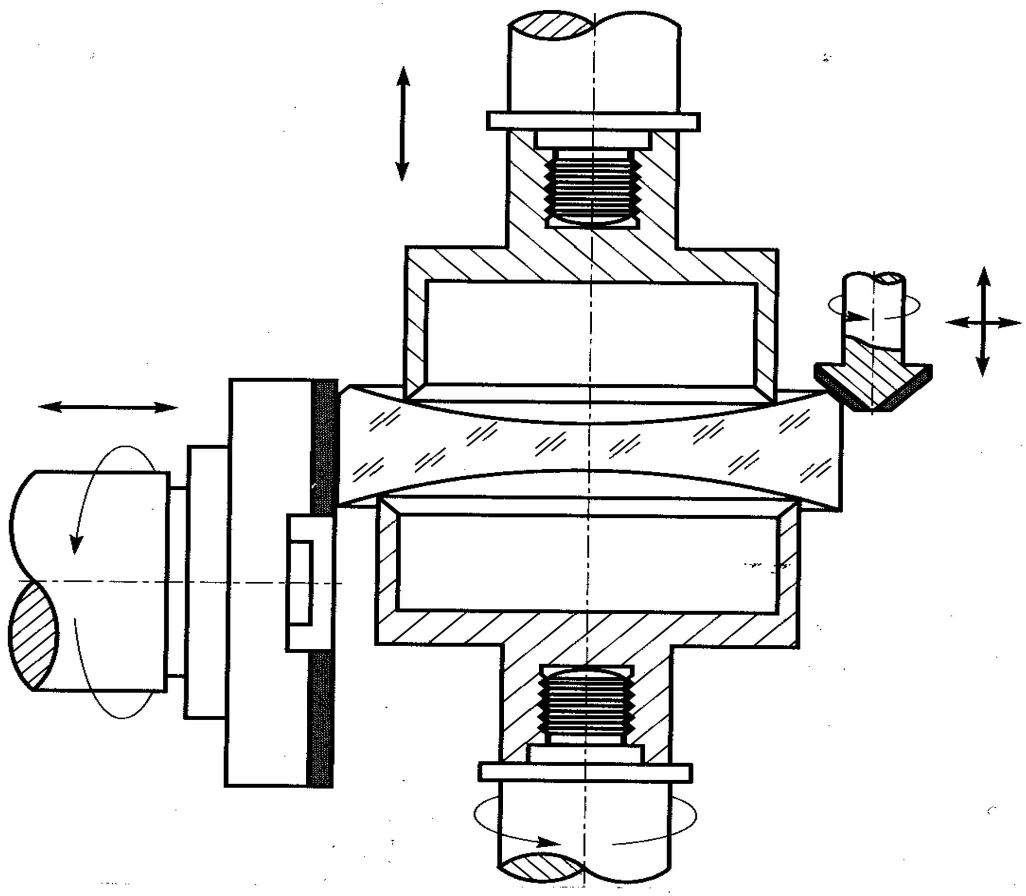


FIG. 6.5. Measurement of run-out of edge cylinder.

Parks & Kimmel ISO 10110 Optics and Optical Instruments – Preparation of Drawings for Optical Elements and Systems: A users Guide Second Edition.

Automatic edging

Clamped between two chucks with common axis,
then outer edge is ground concentric.



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Automatic edging and bevels

Secured and centered on a chuck, then outer edge is ground concentric and features are added

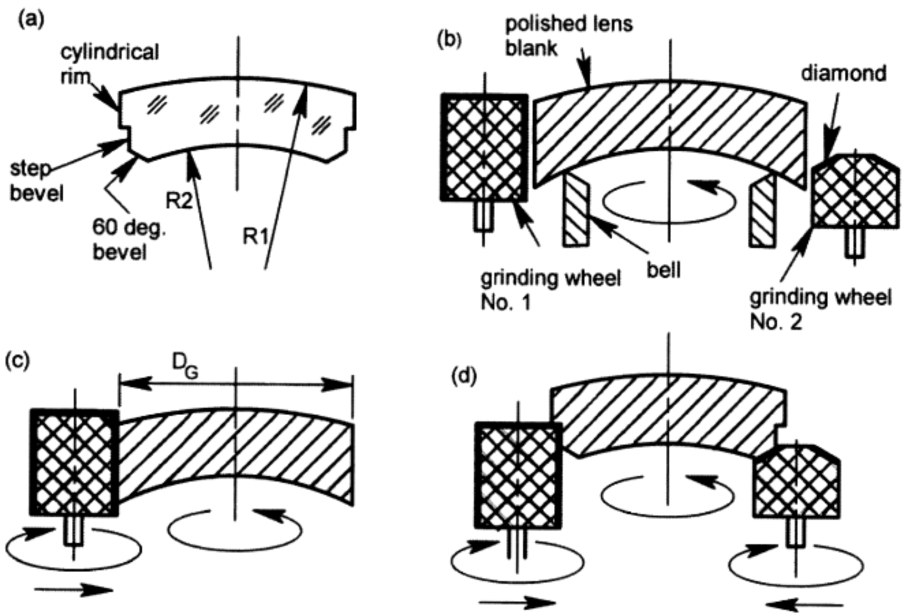
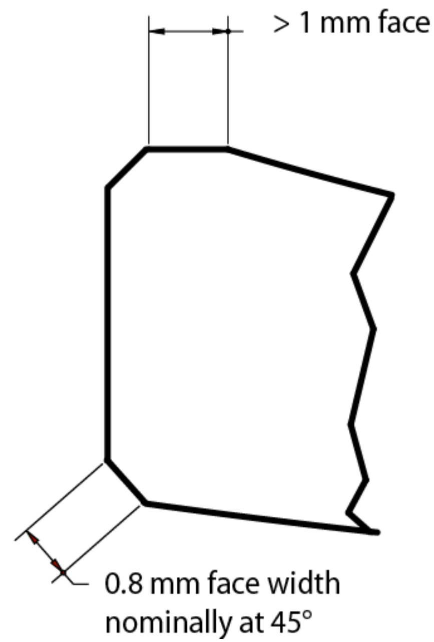


Figure 2.11 Producing various mechanical surfaces in addition to the rim on a lens element during edging.

•Glass corners are fragile. Always use a bevel unless the sharp corner is needed (like a roof). If so, protect it.



Lens diameter	Bevel facewidth
25 mm	> 0.3 mm
50 mm	> 0.5 mm
150 mm	> 1 mm
400 mm	> 2 mm

Design approach for lens mounts

- Lenses are axisymmetric, usually with spherical surfaces
- Key drivers for design are centration and spacing tolerances
- Metal barrels can be machined so they are highly symmetric

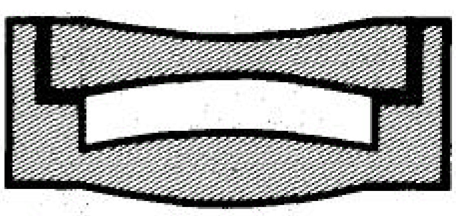
1. Place one lens spherical surface onto a true surface on the barrel. This gives excellent accuracy at low cost.
2. Remaining degree of freedom is centration.

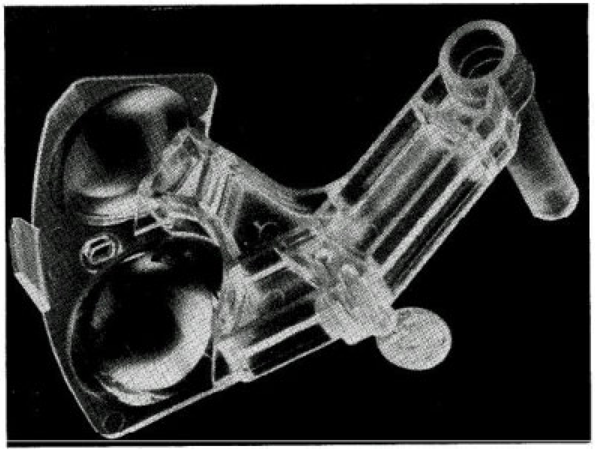
- Control by size of bore, lens, and tight tolerance, clamped or potted in place
  - direct centering error
  - lens wedge

- Lens barrel is critical for control of stray light
  - Balance with optical design to maintain clear aperture, but limit strays
  - Blacken edges of lenses that are illuminated or are viewed
  - Cut threads on inside surfaces, blacken for good rejection
  - Avoid specular reflections into the sensor, even from blackened surfaces
  - Add baffle tube in front of lenses

Plastic lenses

- Optical quality of plastic is inferior to glass
  - Dispersion
  - Stress birefringence
  - Hardness, climatic resistance
  - Stability (thermal, moisture)
- But plastic has important advantages
  - Plastic lenses are manufactured in large quantities by injection molding
    - Cost is $2-20k for tooling, then << $1 per part
  - Lightweight, half the density of glass
  - Ability to create complex shapes
    - Aspheric optical surfaces
    - Diffractive surfaces
    - Incorporate mounting features in the optic itself
    - More complex optical systems





Tolerancing of optical surfaces

- Radius of curvature
  Tolerance on R (0.2% is typical)
  Tolerance on sag (maybe 3 µm = 10 rings)

$$\Delta sag = -\frac{D^2}{8R^2}\Delta R$$

- Conic constant (or aspheric terms)
- Surface form irregularity (figure)
- Surface texture (finish)

  } PSD = A/f ^{B}

- Surface imperfections (cosmetics, scratch/dig)
- Surface treatment and coating

Get nominal tolerances from fabricator

Tolerance for radius of curvature

Surface can be made spherical with the wrong radius.
Tolerance this several ways:

1. Tolerance on R (in mm or %)
2. Tolerance on focal length (combines surfaces and refractive index)
3. Tolerance on surface sag (in µm or rings)

$$sag \cong \frac{\left(D/2\right)^2}{2R}$$

$$\Delta sag = -\frac{D^2}{8R^2}\Delta R$$

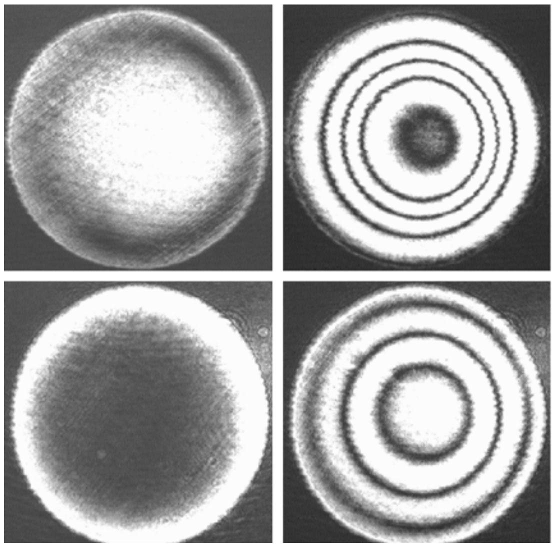
1 ring = $\lambda/2$ sag difference between part and test glass

Test plates

- Most optical surfaces are measured against a reference surface called a test plate
  - The radius tolerance typically applies to the test plate
  - The surface departure from this will then be specified
    i.e. 4 fringes (or rings) power, 1 fringe irregularity
- The optics shops maintain a large number of test plates. It is economical to use the available radii.
- Optical design programs have these radii in a data base to help make it easy to optimize the system design to use them. Your design can then use as-built radii.
- If you really need a new radius, it will cost ~$1000 and 2 – 3 weeks for new test plates. You may also need to relax the radius tolerance for the test plates.

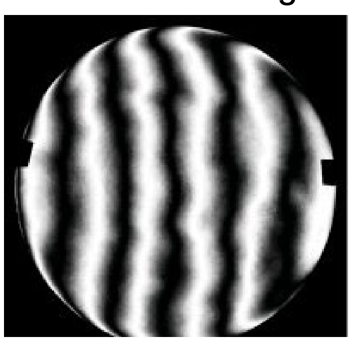
Test plate measurement

Power looks like rings

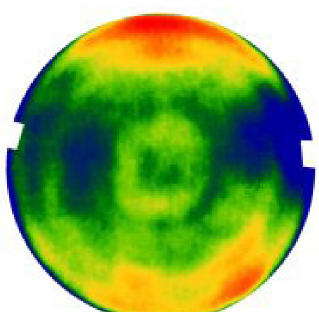


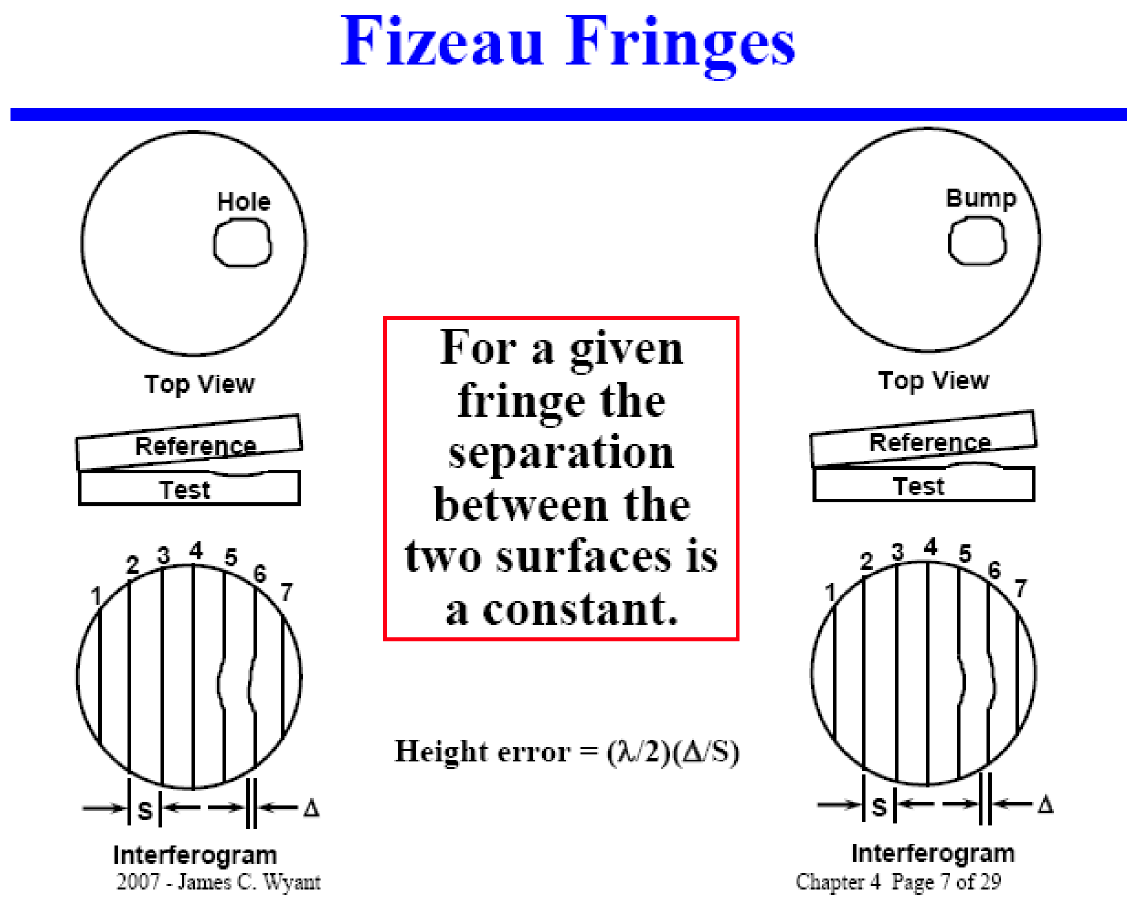
Irregularity

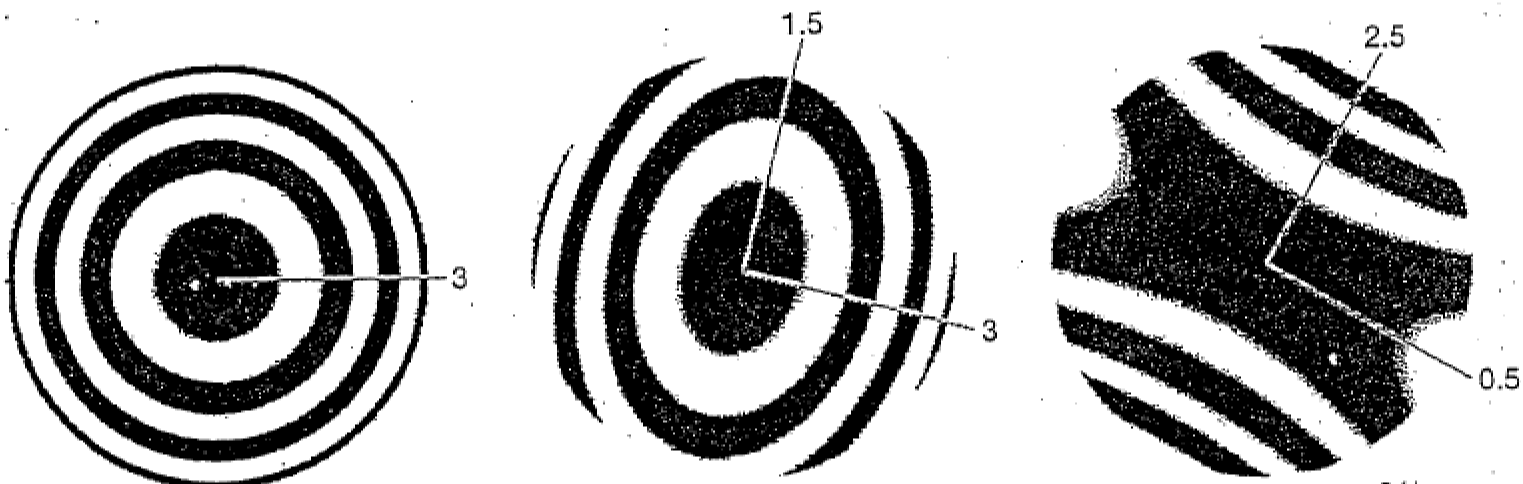
Interferogram



Phase map



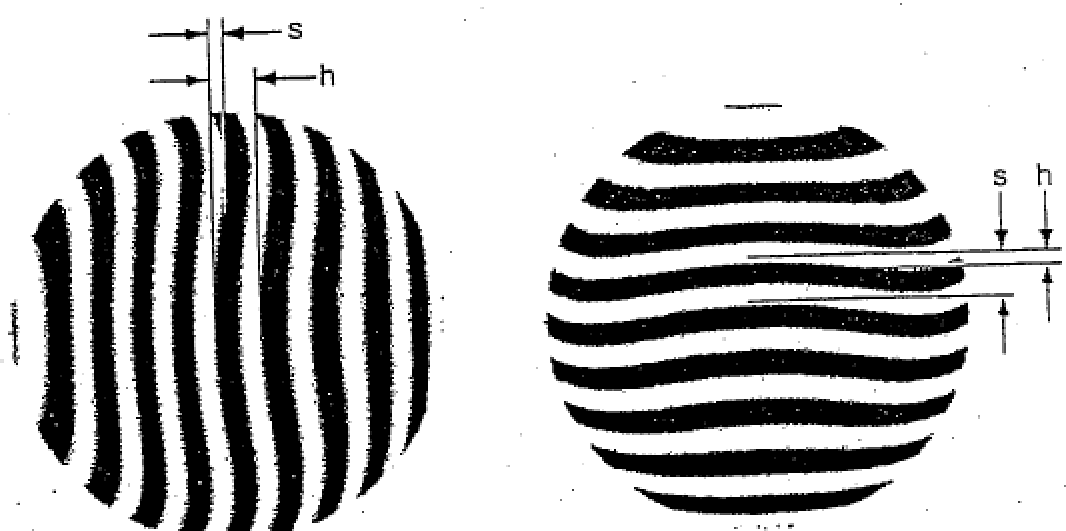




(a) 3 fringe spacings sagitta error

(b) 2,25 fringes sagitta error = (3 + 1,5)/2 — 1,5 fringes irregularity = 3 − 1,5

(c) 1 fringe sagitta error = (2,5 − 0,5) 1/2 — 3 fringes irregularity = 2,5 + 0,5



(d) 0,25 fringe rotationally symmetric irregularity = 0,22/0,88 (= h/s)

(e) 0,25 fringes rotationally symmetric irregularity = 0,22/0,88 (= h/s)

(Covered in 415/515)

Surface figure specification

- Wavefront error = Surface error $\times(n-1)\cos\theta_{incident}$
- Specifications are based on measurement
  - Inspection with test plate.
    Typical spec: 0.5 fringe = $\lambda/4$ P-V surface
  - Measurement with phase shift interferometer.
    Typical spec: 0.05 λ rms
- For most diffraction limited systems, rms surface gives good figure of merit
- Special systems require Power Spectral Density spec
  PSF is of form A/f^B
- Geometric systems really need a slope spec, but this is uncommon. Typically, you assume the surface irregularities follow low order forms and simulate them using Zernike polynomials – rules of thumb to follow…

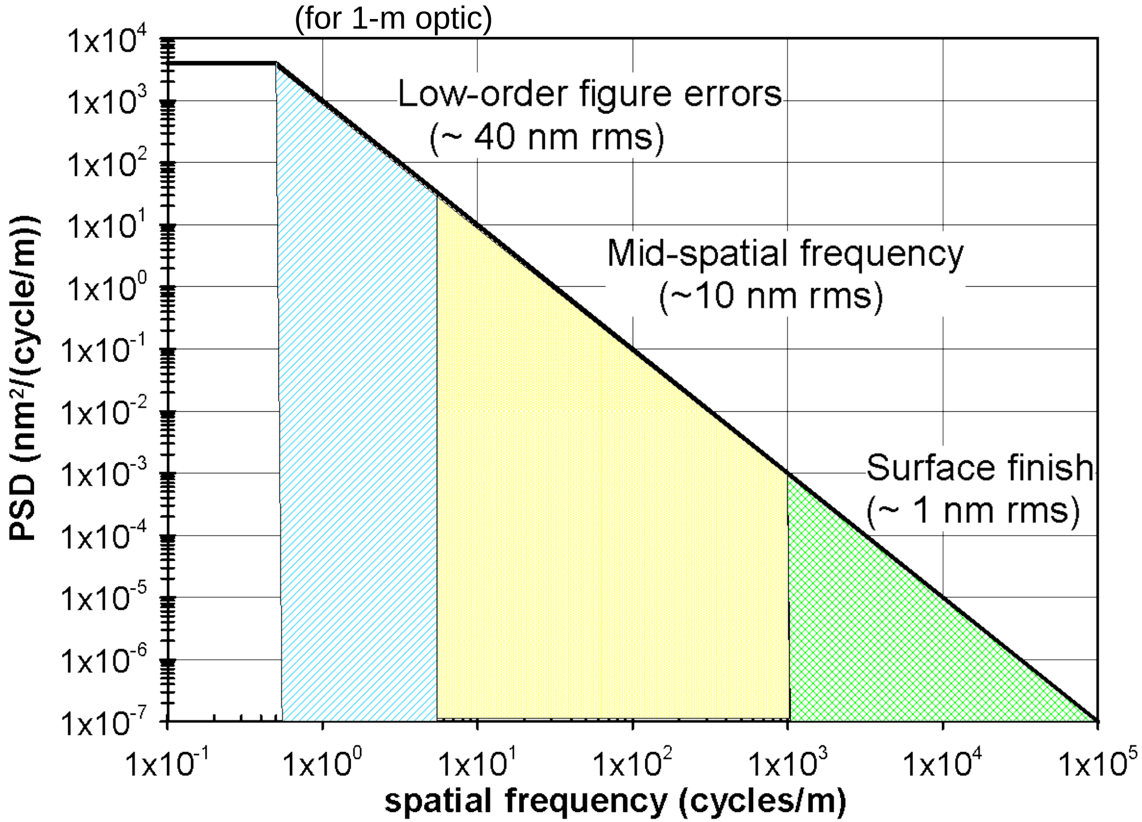
(Covered in 415/515)

Power Spectral Density

High performance systems use PSD to specify allowable surface errors at all spatial frequencies

PSD typically shows mean square surface error as function of spatial frequency. Get rms in a band by integrated and taking the square root

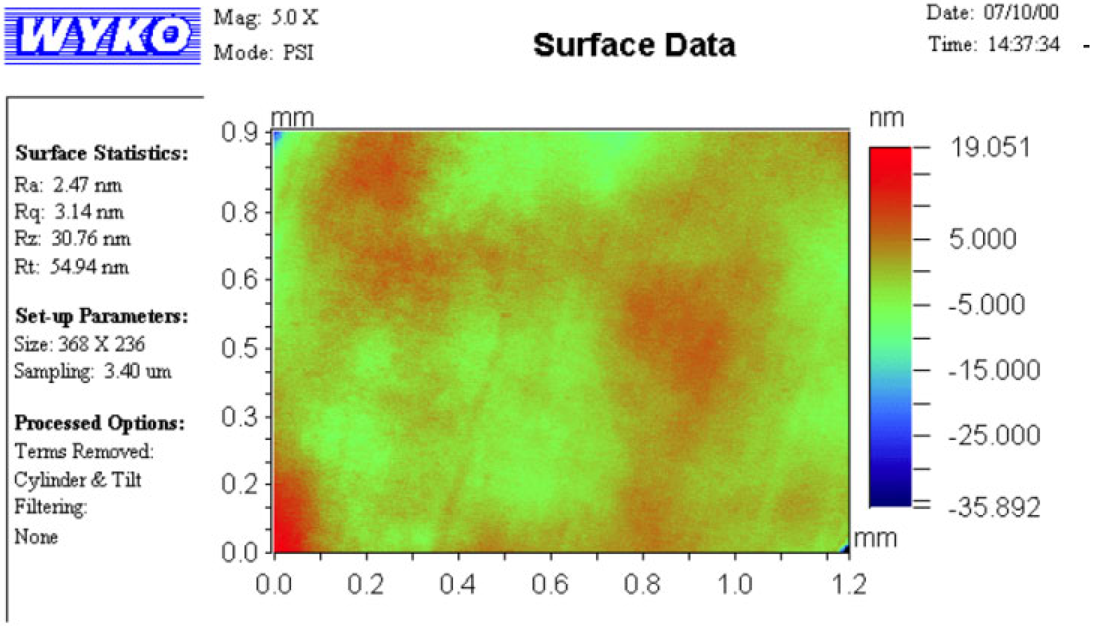
Typical from polishing: PSD = A * f^{-2} *(not valid for diamond turned optics)*



Surface roughness

- Small scale irregularity (sometimes called micro-roughness) in the surface, comes from the polishing process.
- Pitch polished glass, 20 Å rms is typical
- Causes wide angle scatter. Total scatter is σ^2, where σ is rms wavefront in radians.
- Example: for a 20 Å lens surface -> 10 Å wavefront, for 0.5 µm light, σ is 0.0126 rad. Each surface scatters 0.016% into a wide angle

Typical data for a pitch polished surface



(Covered in 415/515)

Effect of small scale errors

Consider figure errors of ΔS nm rms with spatial period L

$$\Delta W = \Delta S(n-1)\cos(\phi)$$

Convert to wavefront, and to radians

$$\sigma = 2\pi\Delta W_{rms} = 2\pi\Delta S(n-1)\cos(\phi)$$

σ^2 of the energy is diffracted out of central core of point spread function

Diffraction angle θ is $\pm\lambda/L$ (where λ is wavelength)

<u>For L<<D</u>

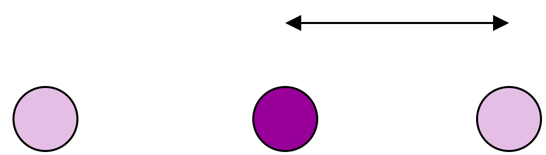
Optical Invariant analysis tells us that the effect in the image plane will be energy at

$$\varepsilon = \pm\theta\,(\alpha D_i)F_n$$

$$= \pm\frac{\lambda\alpha D_i F_n}{L}$$

αD_i is the beam diameter from a single field point on surface *i* under consideration

F_n is the system focal ratio



Each satellite image due to wavefront ripples has energy $\sigma^2/2$ of the main image

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Surface Imperfections

Surface defects are always present at some level in optical surfaces. These consist of scratches, digs (little pits), sleeks (tiny scratches), edge chips, and coating blemishes. In most cases these defects are small and they do not affect system performance. Hence they are often called “beauty specifications”. They indicate the level of workmanship in the part and face it, nobody wants their expensive optics to looks like hell, even if appearance does not impact performance.

In most cases surface defects only cause a tiny loss in the system throughput and cause a slight increase in scattered light. In almost all cases, these effects do not matter. There are several cases that the surface imperfections are more important –

- **Surfaces at image planes**. The defects show up directly.
- **Surfaces that must see high power levels**. Defects here can absorb light and destroy the optic.
- **Systems that require extreme rejection of scattered light**, such as would be required to image dim objects next to bright sources.
- **Surfaces that must have extremely high reflectance**, like Fabry-Perot mirrors.

Scratch Dig spec

The specification of surface imperfections is complex. The most common spec is the scratch/dig specification from MIL-O-13830A. Few people actually understand this spec, but it has become somewhat of a standard for small optics in the United States. A related spec is MIL-C-48497 which was written for reflective optics, but in most cases, MIL-O-13830 is used.

Mil-O-13830A is technically obsolete and has been replaced by Mil-PRF-13830B.

A typical scratch/dig would be 60/40, which means the scratch designation is 60 and the dig designation is 40

The ISO 10110 standard makes more sense, but it has not yet been widely adopted in the US.

(Covered in 415/515)

Rules of thumb for lenses

Optical element tolerances

Parameter	**Base**	**Precision**	**High precision**
Lens diameter	100 µm	25 µm	6 µm
Lens thickness	200 µm	50 µm	10 µm
Radius of curvature Surface sag Value of R	 20 µm 0.5%	 1.3 µm 0.1%	 0.5 µm 0.01% or 2 µm
Wedge (light deviation)	5 arc min	1 arc min	15 arc sec
Surface irregularity	1 wave	λ/4	λ/20
Surface finish	50 Å rms	20 Å rms	5 Å rms
Scratch/dig	80/50	60/40	20/10
Dimension tolerances for complex elements	200 µm	50 µm	10 µm
Angular tolerances for complex elements	6 arc min	1 arc min	15 arc sec
Bevels (0.2 to 0.5 mm typical)	0.2 mm	0.1 mm	µ0.02 mm

Base: 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: Requires special equipment or personnel, may cost 100% more

(Covered in 415/515)

Commercial Chart for Lenses

OPTIMAX® SYSTEMS, INC.
Sales: (877) 396-7846 ▲ Fax (585) 265-1033
www.optimaxsi.com

QUICK	RELIABLE	QUALITY

Optimax provides rapid delivery services for a wide variety of optics ranging in size from 10-100mm. Specifications below are general guidelines for tolerancing prototype optics with optical surfaces of f/1 or slower. Tighter tolerances may be possible depending on part specific size, shape and/or material. Optimax stocks a large inventory of ECO-FRIENDLY preferred glasses, see listing.

ASPHERES ▲ CYLINDERS ▲ PRISMS ▲ SPHERES

OPTICS MANUFACTURING TOLERANCES

ATTRIBUTE	COMMERCIAL QUALITY	PRECISION QUALITY	MANUFACTURING LIMITS
GLASS QUALITY (n_d, v_d)	±0.001, ±0.8%	±0.0005, ±0.5%	Melt controlled
DIAMETER (mm)	+0.00/-0.10	+0.000/-0.025	+0.000/-0.010
CENTER THICKNESS (mm)	±0.150	±0.050	±0.025
SAG (mm)	±0.050	±0.025	±0.010
CLEAR APERTURE	80%	90%	100%
RADIUS	±0.2% or 5 fr	±0.1% or 3 fr	±0.0025mm or 1 fr
IRREGULARITY - Interferometer (fringes)	2	0.5	0.1
IRREGULARITY - Profilometer (microns)	±10	±1	±0.1
WEDGE LENS (ETD, mm)	0.050	0.010	0.002
WEDGE PRISM (TIA, arc min)	±5	±1	0.1
BEVELS (face width @ 45°, mm)	<1.0	<0.5	No Bevel
SCRATCH - DIG (MIL-PRF-13830B)	80 - 50	60 - 40	5-2
SURFACE ROUGHNESS (Å rms)	50	20	2
AR COATING (R_{Ave})	MgF_2 R < 1.5%	BBAR, R < 0.5%	Custom Design

(Covered in 415/515)

Tolerancing for optical materials

- Refractive index value
- Dispersion
- Refractive index inhomogeneity
- Straie
- Stress birefringence
- Bubbles, inclusions

Get nominal tolerances from glass catalogs

Some glasses and sizes come in limited grades.

(Covered in 415/515)

Rules of Thumb for glass properties

Parameter	**Base**	**Precision**	**High precision**
Refractive index departure from nominal	± 0.001 (Standard)	±0.0005 (Grade 3)	±0.0002 (Grade 1)
Refractive index measurement	$\pm 3 \times 10^{-5}$ (Standard)	$\pm 1 \times 10^{-5}$ (Precision)	$\pm 0.5 \times 10^{-5}$ (Extra Precision)
Dispersion departure from nominal	± 0.8% (Standard)	± 0.5% (Grade 3)	±0.2%% (Grade 1)
Refractive index homogeneity	$\pm 1 \times 10^{-4}$ (Standard)	$\pm 5 \times 10^{-6}$ (H2)	$\pm 1 \times 10^{-6}$ (H4)
Stress birefringence (depends strongly on glass)	20 nm/cm	10 nm/cm	4 nm/cm
Bubbles/inclusions (>50 µm) (Area of bubbles per 100 cm^3)	0.5 mm^2 (class B3)	0.1 mm^2 (class B1)	0.029 mm^2 (class B0)
Striae Based on shadow graph test	Normal quality (has fine striae)	Grade A (small striae in one direction)	Precision quality (no detectable striae)

(Ref. Schott catalog)

(Covered in 415/515)

Conventions, standards,…

- There now exists international standards for specifying optical components. ISO-10110.
- The ISO standards provide a shortcut for simplifying drawings. When they are used correctly, they allow technical communication across cultures and languages
- Use *ISO 10110 --- Optics and Optical Instruments Preparation of drawings for optical elements and systems, A User's Guide 2nd Edition,* by Kimmel and Parks. Available from OSA.
- The ISO standards are not widely used in the US, and will not be emphasized in this class.

(Covered in 415/515)

ISO 10110 --- Optics and Optical Instruments
Preparation of drawings for optical elements and systems

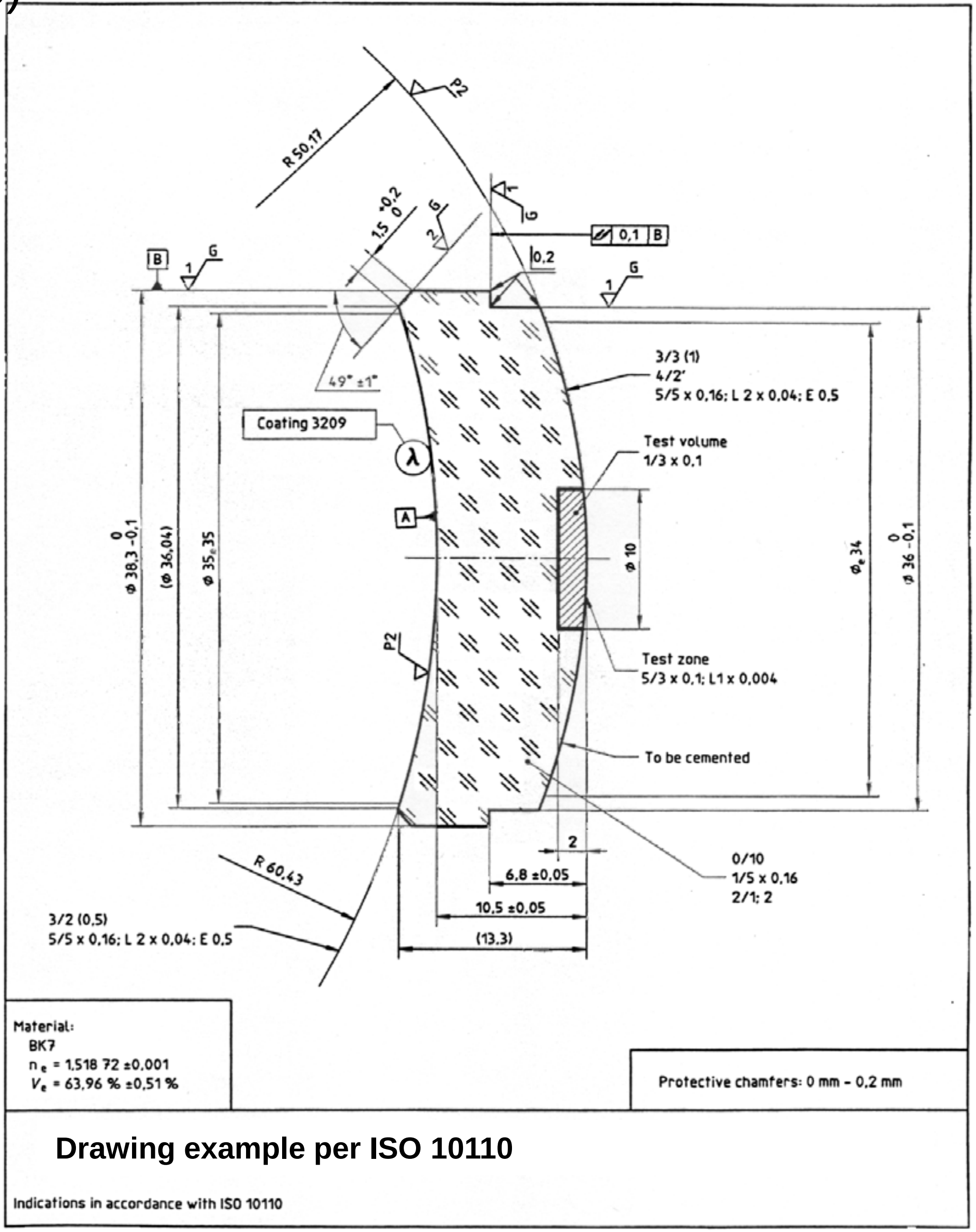
- 13 part standard
  - 1. General
  - 2. Material imperfections -- Stress birefringence
  - 3. Material imperfections -- Bubbles and inclusions
  - 4. Material imperfections -- Inhomogeneity and striae
  - 5. Surface form tolerances
  - 6. Centring tolerances
  - 7. Surface imperfection tolerances
  - 8. Surface texture
  - 9. Surface treatment and coating
  - 10. Tabular form
  - 11. Non-toleranced data
  - 12. Aspheric surfaces
  - 13. Laser irradiation damage threshold
- available from ANSI 212-642-4900
- Better yet, User's Guide is available from OSA

(Covered in 415/515)

ISO 10110 --- Optics and Optical Instruments
Preparation of drawings for optical elements and systems

- Codes for tolerancing

0/A	Birefringence, A is max nm/cm OPD allowed
1/N x A	Bubbles and inclusions, allowing N bubbles with area A
2/A;B	Inhomogeneity class A, straie class B
3/A(B/C)	sagitta error A, P-V irregularity B, zonal errors C (all in fringes)
4/σ	σ is wedge angle in arc minutes
5/N x A	Surface imperfections, N imperfections of size A
CN x A	Coating imperfections, N imperfections of size A
LN x A	Long scratches, N scratches of width A µm
EA	Edge chips allowed to protrude distance A from edge
5/TV	Transmissive test, achieving visibility class V
5/RV	Reflective test, achieving visibility class V
6/H	Laser irradiation energy density threshold H



Drawing example per ISO 10110

(Covered in 415/515)

Standards

General, physical dimensions

ISO-10110-1 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 1: General

ISO-10110-6 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 6: Centring tolerances

ISO-10110-10 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 10: Tabular form

ANSI Y14.5M Dimensioning and tolerancing

ISO 7944 Reference wavelength

ISO 128 Technical drawings – General principles of presentation

ISO 406, Technical drawings – Tolerancing of linear and angular dimensions

ISO 1101, Technical drawings – Geometrical tolerancing – form, orientation, run-out

ISO 5459, Technical drawings – Geometrical tolerancing – datums and datum systems

ISO 8015, Technical drawings – Geometrical tolerancing – fundamental tolerancing principle for linear and angular tolerances

DIN 3140 Optical components, drawing representation figuration, inscription, and material. German standard, basis of ISO 10110

MIL-STD-34 Preparation of drawings for optical elements and systems: General requirements, *obsolete*

ANSI Y14.18M Optical parts

Optical surfaces

ISO-10110-5 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 5: Surface form tolerances

ISO-10110-7 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 7: Surface imperfection tolerances

ISO-10110-8 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 8: Surface texture

ISO-10110-12 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 12: Aspheric surfaces

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Mil-O-13830A, Optical components for fire control instruments; General specification governing the manufacture, assembly, and inspection of.

ANSI PH3.617, Definitions, methods of testing, and specifications for appearance imperfections of optical elements and assemblies

ISO 4287 Surface roughness – Terminology

ISO 1302 Technical drawings – Method of indicating surface texture on drawings

ANSI Y14.36 Engineering drawing and related documentation practices, surface texture symbols

More Standards

Material imperfections

ISO-10110-2 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 2: Material imperfections – stress birefringence

ISO-10110-3 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 3: Material imperfections – bubbles and inclusions

ISO-10110-4 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 4: Material imperfections – inhomogeneity and striae

MIL-G-174 Military specification – Optical glass

Coatings

ISO-10110-9 Optics and optical instruments – Preparation of drawings for optical elements and systems – Part 9: Surface treatment and coating
ISO 9211-1, Optics and optical instruments – Optical coatings – Part 1: Definitions
ISO 9211-2, Optics and optical instruments – Optical coatings – Part 2: Optical properties
ISO 9211-3, Optics and optical instruments – Optical coatings – Part 3: Environmental durability
ISO 9211-4, Optics and optical instruments – Optical coatings – Part 4: Specific test methods
MIL-C-675 Coating of glass optical elements
MIL-M-13508 Mirror, front surface aluminized: for optical elements
MIL-C-14806 Coating, reflection reducing, for instrument cover glasses and lighting wedges
MIL-C-48497 Coating, single or multilayer, interference, durability requirements for
MIL-F-48616 Filter (coatings), infrared interference: general specification for

(Covered in 415/515)

Even more standards

Measurement, inspection, and test

ISO 9022: Environmental test methods

ISO 9039: Determination of distortion

ISO 9211-4, Optics and optical instruments – Optical coatings – Part 4: Specific test methods

ISO 9335: OTF measurement principles and procedures

ISO 9336: OTF, camera, copier lenses, and telescopes

ISO 11455: OTF measurement accuracy

ISO 9358: Veiling glare, definition and measurement

ISO 9802: Raw optical glass, vocabulary

ISO 11455: Birefringence determination

ISO 12123: Bubbles, inclusions; test methods and classification

ISO 10109: Environmental test requirements

ISO 10934: Microscopes, terms

ISO 10935: Microscopes, interface connections

ISO 10936: Microscopes, operation

ISO 10937: Microscopes, eyepiece interfaces

ASTM F 529-80 Standard test method for interpretation of interferograms of nominally plane wavefronts

ASTM F 663-80 Standard practice for manual analysis of interferometric data by least-squares fitting to a plane reference surface

ASTM F 664-80 Standard practice for manual analysis of interferometric data by least-squares fitting to a spherical reference surface and for computer-aided analysis of interferometric data.

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