Optics Rules of Thumb

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What is a rule of thumb?

- A simple rule that guides your work
- A simple calculation that provides you immediate solution and answer!
  - make first order approximations, e.g. sin(A)=tan(A)=A
- A number that helps you make design decision
  - Order of magnitude of some optical and mechanical properties
  - Manufacturing capability

Photonics Rules of Thumb

- For quick and easy reference, this is a handy compilation of proven photonics calculations that cover the full range of photonics, from optics to lasers and detectors. These simple-to-implement calculations and rules let you keep your composure and provide immediate solutions and answers. This is a succinct, handy, and unique reference for anyone working in the optical sciences. Many of these rules have been used in the industry for years, but this is the first time they have been systematically collected. While providing a light-hearted guide to the lost art of estimation, it also shows how you can quickly predict the impact of changes. You'll develop a sense of what will work and what won't, and be able to explain why.

How to use a rule of thumb?

Memorize it!

Know the limit of application!

Contents

- General rules of thumb
- Rules of thumb mentioned in previous talks
- Rules of thumbs I often used

General rules

- Murphy's law:
  If anything can go wrong, it will!

  Don't take chances!

- Have a backup plan!
- Think twice before touching anything that has been aligned
- Dirty optics should be cleaned only after great deliberation and with great caution

Figure of Merits

Domain	**Geometric limit**	**Near Diffraction Limited**
Criteria in WFE	>1λ	~λ/4
Figure of Merit	RMS spot size	RMS WFE

Strehl ratio:

When Wrms=0.07, SR=0.8

$$SR \approx 1-(2\pi W_{rms})^2$$

Diffraction spot diameter:

$$d = \frac{1.22\lambda}{NA} = 2.44\lambda F_n$$

Total scattering loss:

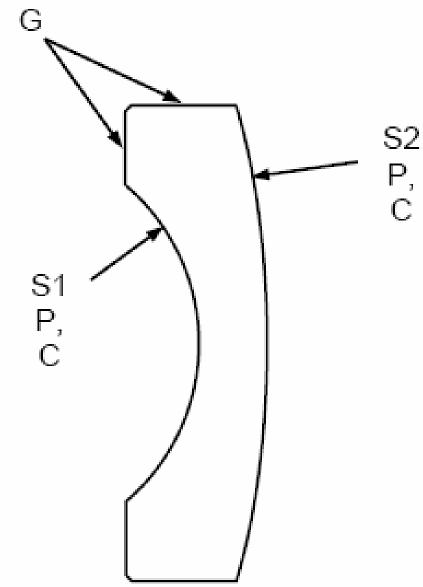
σ: surface roughness in λ

$$TIR = \frac{I_{scat}}{I_{tot}} = 1-(2\pi\sigma)^2$$

Lens drawing

	Radius	Radius tolerance	Power/ Irreg.	Clear aper. diameter.
S	13.589	TPF	5/3	20.6
S	64.643	TPF	5/3	29.0

Edge diameter	Diameter tolerance	CT	Thickness tolerance	Wedge
31.18	±0.05	4.45	±0.05	0.05



Notes:

1. All dimensions in inches.
2. Material: Optical glass per MIL-G-174 type BK7
   Schott No. 517642
   nd = 1.5168 ± 0.0005 V = 64.2 ± 0.8% striae
   Grade A, fine anneal
3. Surfaces marked "P" polish to power / irregularity indicated
4. Manufacturer per mil-0-13830
5. Surface quality 60 - 40
6. Surfaces marked "C" coat with high efficiency coating with average reflectance per surface ≤ 0.5% from 420 - 680 nm
7. Surface marked "G" fine grind and blacken with no buildup
8. Bevel edges at 45 degrees to 0.5 max face width
9. Diameter to flat is 19.952 (REF) with surface sag of 5.977 ±0.05 on surface S1

DR	
CHK	
APP	
SCALE -	

Sample Element

Optical element tolerances

Parameter	**Base**	**Precision**	**High precision**
Lens diameter	100 µm	12 µm	6 µm
Lens thickness	200 µm	50 µm	10 µm
Radius of curvature (tolerance on sag)	20 µm	1.3 µm	0.5 µm
Wedge (light deviation)	6 arc min	1 arc min	15 arc sec
Surface irregularity	5 fringes	1 fringe	0.25 fringe
Surface finish	50 Å rms	20 Å rms	5 Å rms
Scratch/dig	160/100	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	0.02 mm

Base: typical, no cost impact for reducing tolerances beyond this
Precision: readily available, may cost 25% more
High precision: need special equipment or personnel, may coat 100% more

Optical material tolerances

Parameter	**Base**	**Precision**	**High precision**
Refractive index departure from nominal	± 0.001	±0.0005	±0.0002
Refractive index measurement	$\pm 3 \times 10^{-5}$	$\pm 1 \times 10^{-5}$	$\pm 0.5 \times 10^{-5}$
Dispersion departure from nominal	± 0.8%	± 0.5%	±0.2%
Refractive index homogeneity	$\pm 1 \times 10^{-4}$	$\pm 5 \times 10^{-6}$	$\pm 1 \times 10^{-6}$
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	0.1 mm^2	0.029 mm^2
Striae Based on shadow graph test	Normal quality	Precision quality	Precision quality

optical element mounting tolerances

Parameter	Base	Precision	High precision
Spacing (manual machined bores or spacers)	200 µm	25 µm	6 µm
Spacing (NC machined bores or spacers)	50 µm	12 µm	2.5 µm
Concentricity (if part must be removed from chuck between cuts)	200 µm	100 µm	25 µm
Concentricity (cuts made without de-chucking part)	200 µm	25 µm	5 µm

Mechanical Machining Precisions

- 1mm: coarse
- 0.25mm: standard precision
- 0.025mm: precision machining
- 0.002mm: high precision machining

Scratch/dig

- 80-50: commonly acceptable cosmetic standard
- 60-40: acceptable for most scientific research applications
- 40-20: Scattered light can begin to affect system performance
- 10-5: a precision standard for very demanding laser applications

Coating

- Bare surface reflection at normal incidence: $$r = \frac{n-1}{n+1}$$
- Single layer quarter wave AR coating: $$n_c = \sqrt{n_{sub}}$$
  - When $n=1.5$, $n_c=1.38$ (MgF_2), $R \cong 1\%$
- Multi-layer AR coating achieves low reflection (<1%) over a broad spectrum
- V-coating: reflectivity < 0.1% at design wavelength

Metallic Coating

Coating Type	Wavelength Range (nm)	Average Reflectance (%)
Aluminum	400-1200	90
Protected Aluminum (Si2O3 layer, half wave)	400-800	87
Enhanced Aluminum (multi-layer dielectric)	450-750	93
UV-Enhanced Aluminum (UV transmitted dielectric)	250-400	86
Internal Silver (an additional layer of either Inconel or copper).	400-1200	98
Protected Silver	400-20,000	95
Bare Gold	700-20,000	99
Protected Gold (hard dielectrics)	650-16,000	98

Plastic optics

- Avoid flat or weak surfaces
- Dn/dt ~ -100ppm/°C
- CTE ~ 70ppm/ °C
- In comparison:
  - For BK7: dn/dt = 1.4ppm/ °C, CTE = 7.1ppm/ °C
  - For germanium: dn/dt = 396ppm/ °C, CTE = 6ppm/ °C

Thermal impact on focal length

Focal length: $$F = \frac{n-1}{r}$$

$$\Delta F = (\alpha - \frac{1}{n-1}\frac{dn}{dt})F\Delta T = -\nu F \Delta T$$

$$\nu = \frac{1}{n-1}\frac{dn}{dt} - \alpha$$

$$\nu \approx 2\frac{dn}{dt} - \alpha$$ in visible range

Allowable focus shift for diffraction limited performance:

$$\Delta z = 2\lambda F_n^2$$

Material	**ν (x10^{-6})**
Plastic	-237
BK7	-4.4
BaK4	0.3
BaK50	-11.4
SK16	3.4
SF4	-3.8
Germanium	127
ZnSe	35

CTE for Typical Materials

Material	CTE ($\times 10^{-6}$/°C)
Aluminum	23
Steel	10
Invar	0.6
Zerodour	0.02
ULE	0.03

Useful numbers

- 1 arcsec = 5 urad
- 1 mdeg = 3 arcsec
- 1 degree = 1/60 radian
- 1 inch = 25.4mm
- C = 3E8 m/s
- V = 6E14Hz

Laser

- Coherence length $$CL = \frac{\lambda^2}{\Delta\lambda}$$
- Far field diffraction angle: $$\alpha = \frac{\lambda}{D}$$
  - D: aperture size
- Gaussian Beams:
  - Waist: σ
  - Rayleigh range: $$Z_R = \frac{4\pi}{\lambda}\sigma^2$$
  - Divergence: $$\theta = \frac{\lambda}{\pi\sigma}$$

Diode laser

- Astigmatism: 6~8nm
- Divergence: 30x10 degrees FAHM
- Polarization: along the short axis
- Spectrum width: ~1nm
- Lasing wavelength increases as temperature increases

Aberrations of a conic surface

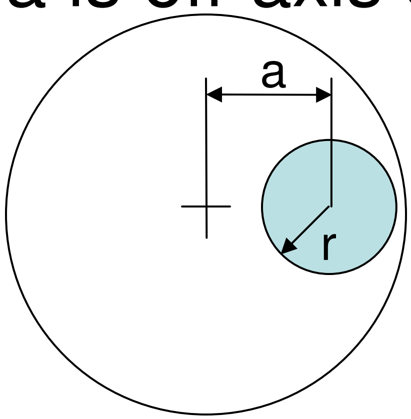
- Spherical aberration of a conic surface:
  - K: conic constant
  - R: vertex radius of curvature

$$SA = \frac{Kr^4}{8R^3}$$

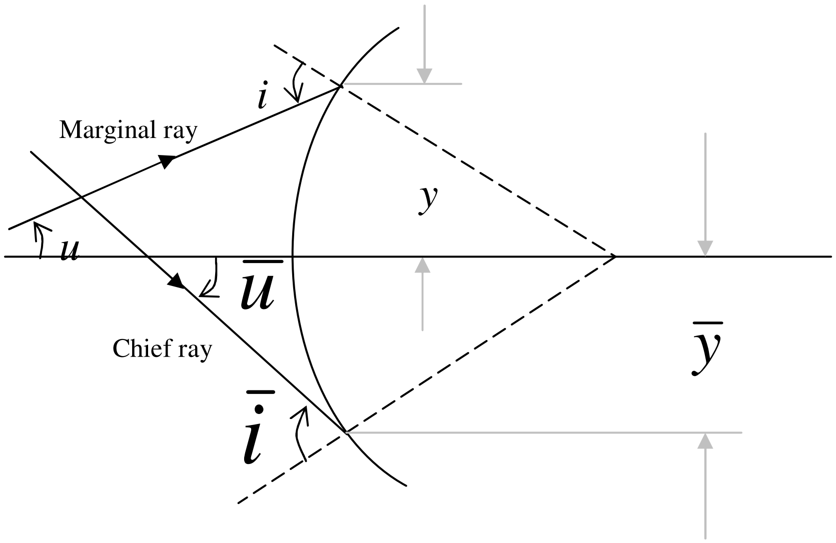
- Aberrations of off-axis conic surfaces:
  - a is off-axis distance

$$COMA = \frac{Kr^3 a}{2R^3}$$

$$ASTI = \frac{Kr^2 a^2}{2R^3}$$



Seidel formulas



$$A = ni$$

$$\bar{A} = n\bar{i}$$

$$\mathrm{H} = n\bar{u}y - nu\bar{y}$$

SA (W_{040}): $S_I = -\sum A^2 y \Delta(\frac{u}{n})$

Coma (W_{131}): $S_{II} = -\sum A\bar{A} y \Delta(\frac{u}{n})$

Asti (W_{222}): $S_{III} = -\sum \bar{A}^2 y \Delta(\frac{u}{n})$

Petzval Curvature (W_{220P}): $S_{IV} = -\sum H^2 c \Delta(\frac{1}{n})$

Distortion(W_{311}): $S_V = \frac{\bar{A}}{A}(S_{III} + S_{IV})$

Axial color: $C_I = Ay\Delta(\frac{\delta n}{n})$

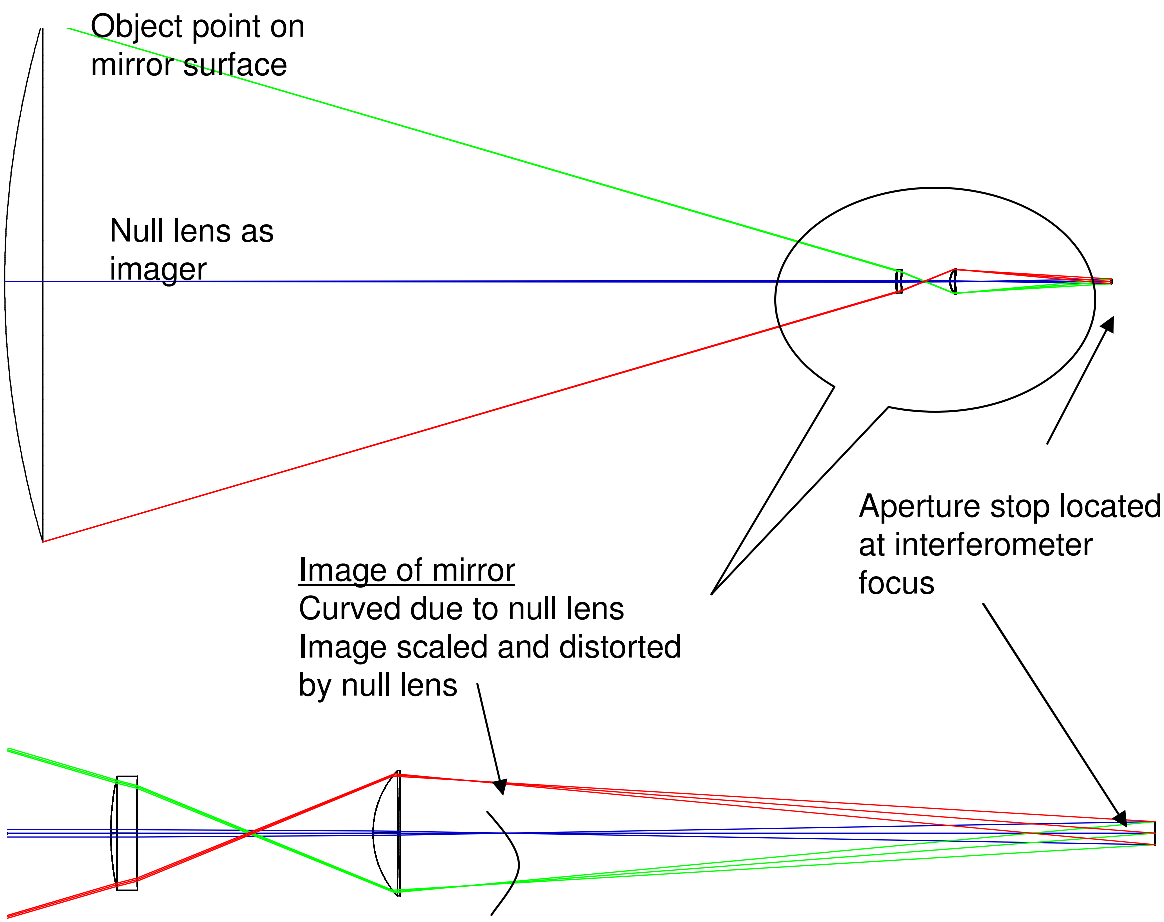
Transverse color: $C_{II} = \bar{A}y\Delta(\frac{\delta n}{n})$

Petzval Curvature

$$P = \Sigma C \Delta(\frac{1}{n}) = \Sigma \frac{\phi}{n}$$

- Complexity of lithography lenses is believed to be caused by effort of correction of Petzval curvature
- Positive lens has positive PC, while positive mirror has negative PC
- Diffractive elements on flat substrate has no PC

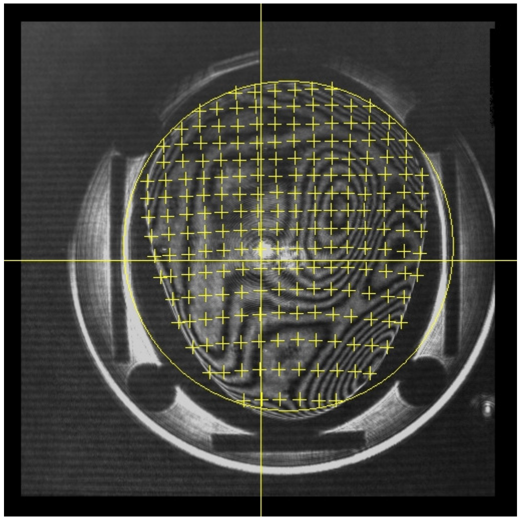
Interferometer is an imaging system too!



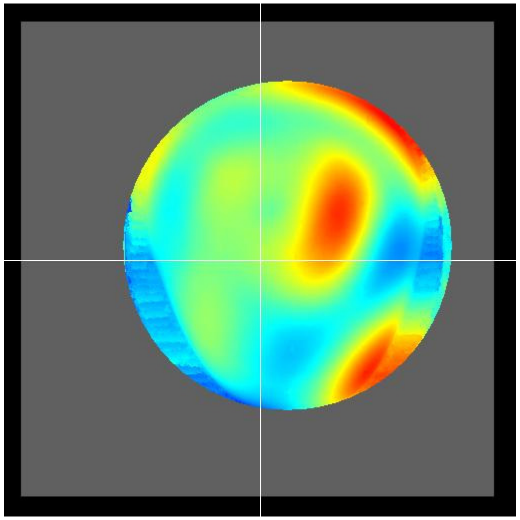
- Aberrations that matter:
  - Distortion
  - Astigmatism
  - Field curvature

Distortion correction – morphing

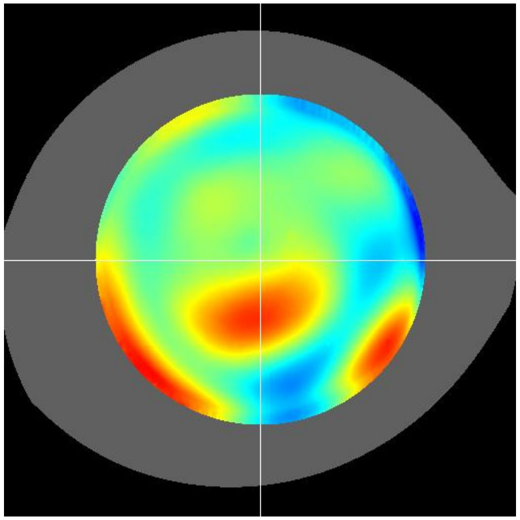
Interferogram



Phase map
before morphing

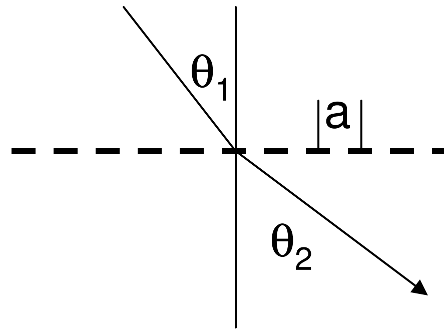


Phase map
after morphing



Grating equation

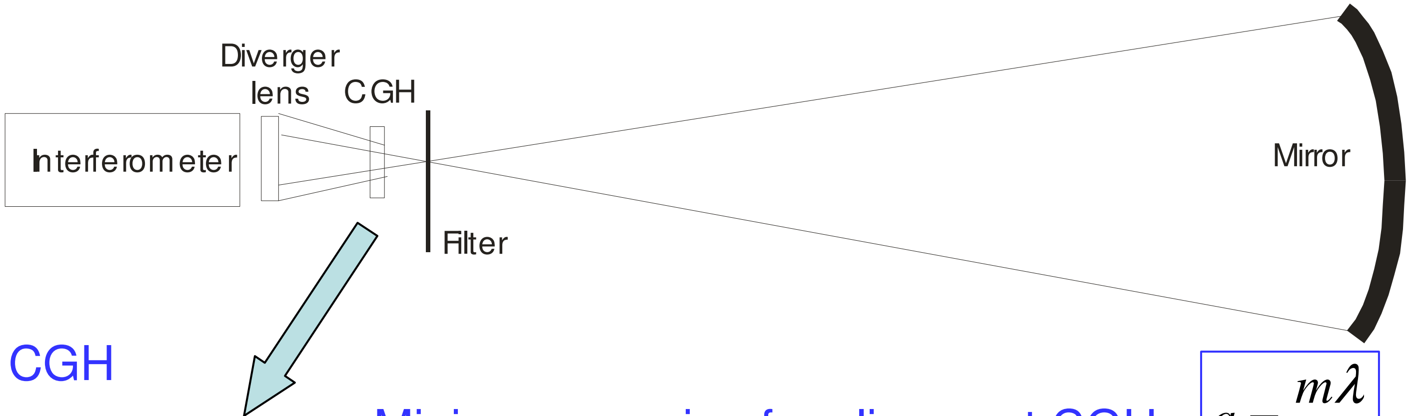
$$n_2 \sin\theta_2 - n_1 \sin\theta_1 = m\frac{\lambda}{a}$$

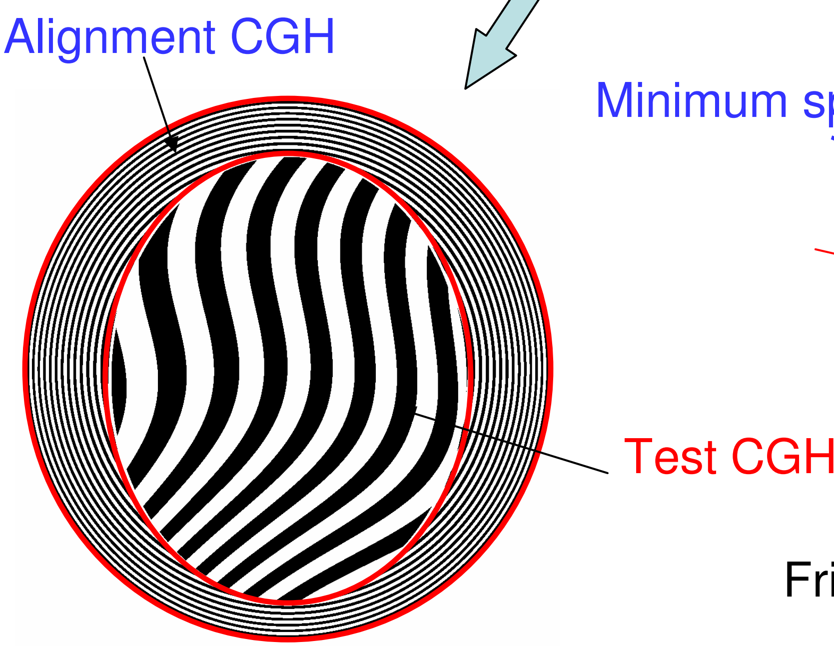


- Approximation:

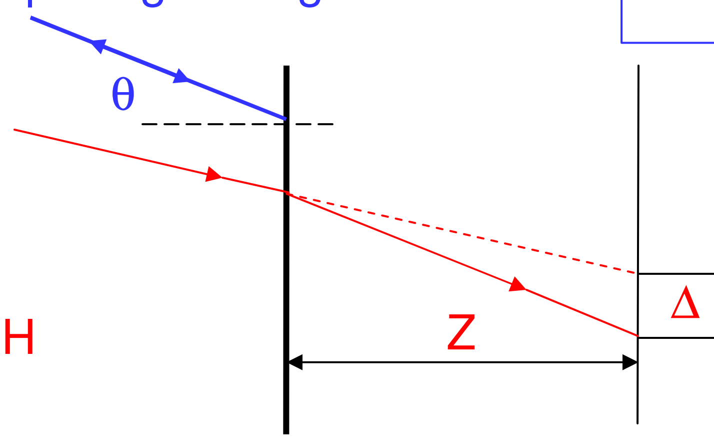
$$\Delta\theta = m\frac{\lambda}{a}$$

Optical testing with CGH





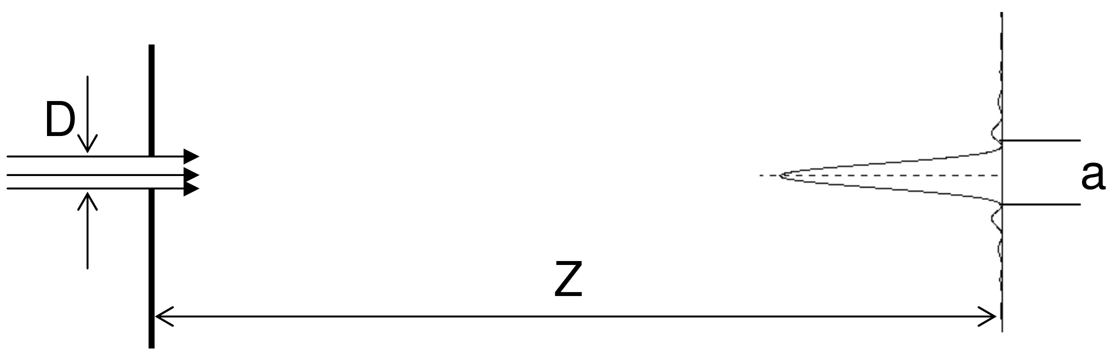
Minimum spacing for alignment CGH: $a = \dfrac{m\lambda}{2\theta}$



Fringe spacing for test CGH (1st order): $a' = \dfrac{Z}{\Delta}\lambda$

Diffraction

- Longitudinal dimensions
  - Wavelength λ and Distance Z
- Transverse dimensions
  - Slit width D and Beam width a at the observation plane

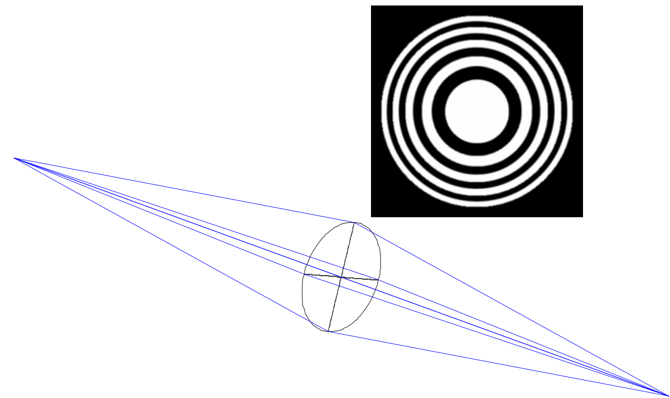


$$\lambda Z \propto Da$$

Diffraction

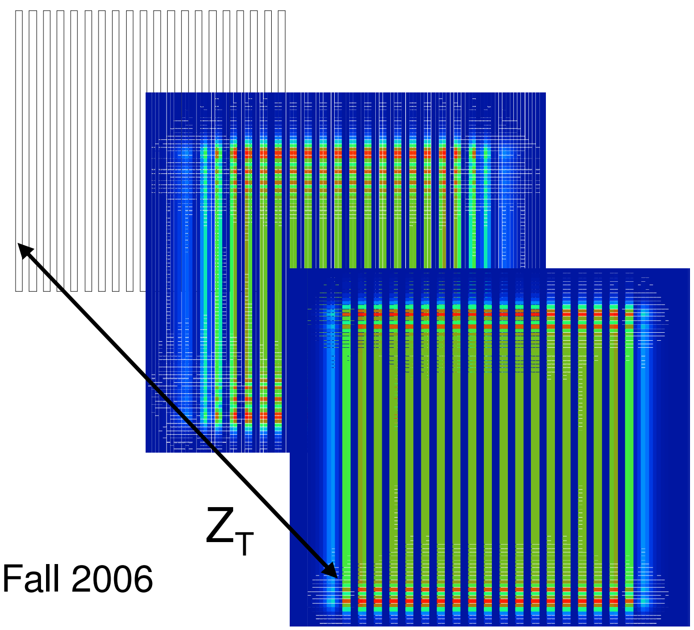
- Fresnel zone plate
  - nth zone radius:

$$r_n^2 = n\lambda f$$



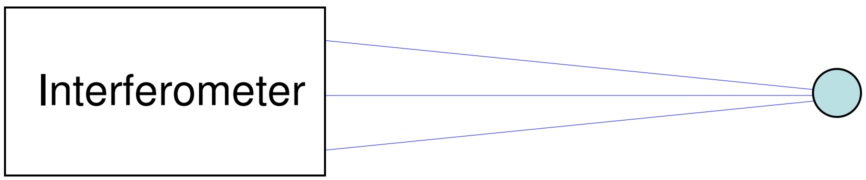
- Talbot distance:

$$Z_T = \frac{2d^2}{\lambda} \Longrightarrow 2d^2 = \lambda Z_T$$



Ball alignment

- Align a ball interferometrically



F_n: Beam f number
R: Ball ROC
ΔL: Ball axial misalignment
ΔT: Ball lateral misalignment

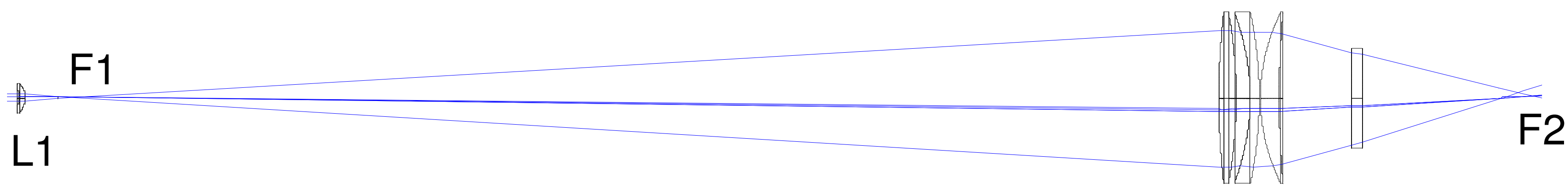
$$Power = 2 \cdot \frac{\Delta L}{8F_n^2}$$

$$Tilt = 2 \cdot \frac{\Delta T}{F_n}$$

$$BeamWalkOff\,\% = 2 \cdot \frac{\Delta T}{R} F_n \cdot 100\%$$

Longitudinal magnification

$$m_{long} = m_{trans}^2$$



- If Lens L1 moves in 3 DOF, how much will Focus F2 move?

Conclusion

- Optical rules of thumbs help you avoid common mistakes and work efficiently
- Have your own list of rules of thumb!