Tolerancing Optical Systems

- Why are tolerances important?
  - Somebody is going to make it (hopefully)
  - It must meet some performance requirement
  - Cost (and schedule) are always important

- Why is it difficult?
  - Involves complex relationships across disciplines
    - System engineering
    - Optical design and analysis
    - Optical fabrication
    - Opto-mechanical design
    - Mechanical fabrication

- If you can tolerance effectively, then you can be a good designer, otherwise you are not.

Process of optical system tolerancing

1. Define quantitative figures of merit for requirements
2. Estimate component tolerances
3. Define assembly/alignment procedure and estimate tolerances
4. Calculate sensitivities, estimate performance
5. Adjust tolerances, keeping cost and schedule in mind
6. Iterate with system engineer, fabricators, management
7. Make drawings with tolerances -- verify them!

System Figure of Merit

- Keep this as simple as possible
- Must propagate all performance specs through assembly
- Typical requirements
  - *RMSWE (root mean square wavefront error)*
  - *MTF at particular spatial frequencies*
  - *Distortion*
  - *Fractional encircled energy*
  - *Beam divergence*
  - *Geometric RMS image size*
  - *Dimensional limits*
  - *Boresight*

Parameters to tolerance

- General parts (usually machined metal)
- Physical dimensions of optical elements
- Optical surfaces
- Material imperfections for optics
- Optical assembly

Estimate system performance

For a merit function that uses RSS to combine independent contributions:

$$\Phi = \sqrt{\Phi_0^2 + \left(\Delta\Phi_1\right)^2 + \left(\Delta\Phi_2\right)^2 + \ldots}$$

Φ_0 is from design residual – simulation of system with no manufacturing errors

$\Delta\Phi_i$ is effect from a single parameter having an error equal to its tolerance

Combining multiple sources of error

There are usually many things that can go wrong that will affect system performance. To calculate the combined effect:

<u>If the causes are independent:</u>

Combine the effects as a root-sum-square

For example:

10 µrad pointing from element 1
15 µrad pointing from element 2
5 µrad pointing from element 3

Combined effect:

$$\sqrt{10^2 + 15^2 + 5^2}$$

$$= \sqrt{100 + 225 + 25}$$

$$= \sqrt{350}$$

$$= 18.7$$

Some interesting things about RSS combination

1. The RSS is dominated by the biggest contributors
2. The smallest contributors are negligible
3. For *N* equal contributions, the RSS is equal to $\sqrt{N}$ times an individual contribution.

Examples:

1. Compute RSS of 10, 1, 2, 1, 1
   = sqrt(100+1+4+1+1)
   =10.3

(not much different from 10)

2. Compute RSS of 10, 11, 10
   = sqrt(100+121+100)
   = 17.9

Now add another term of 2
rss = sqrt(100+121+100 + 4)
=18.0

Not much different from 17.9

3. Compute RSS for *N* equal contributions of *x*:

$$RSS = \sqrt{x^2 + x^2 + x^2 + x^2 + \ldots (N\, times)}$$

$$= \sqrt{N\left(x^2\right)}$$

$$= \sqrt{N} \cdot x$$

Calculate sensitivities

- Define merit function Φ
- Make list of parameters to tolerance, x_1, x_2, x_3, …
  all of the things that will go wrong.
- Use simulation to calculate the effect of each of these on the system performance.
  - For each x_i, find sensitivity by perturbation

$$\frac{\partial \Phi}{\partial x_i} = \frac{\sqrt{\left(\Phi(x_i + \Delta x_i)\right)^2 - \Phi_0^2}}{\Delta x_i}$$

Φ_0 is for unperturbed system (assume uncorrelated with perturbation)

Δx_i is perturbation (by the expected tolerance)

Using compensators

For most optical systems, a final focus adjustment will be made after the system is assembled. The tolerance analysis must take this into account.

When calculating the effect of each perturbation, you simulate this adjustment:

- simulate sensing the error
- adjust the appropriate parameter

This can be used for other degrees of freedom

Always make the simulation follow the complete procedure.

Combining different effects

Calculate system merit function from sensitivities using RSS

$$\Phi = \sqrt{\Phi_0^2 + \left(\frac{\partial \Phi}{\partial x_1} \cdot \sigma_1 \right)^2 + \left(\frac{\partial \Phi}{\partial x_2} \cdot \sigma_2 \right)^2 + \ldots}$$

σ_i is now the tolerance for x_i which could be adjusted

Put the sensitivities into a spreadsheet to allow easy calculation of the system errors with all effects.

Spreadsheet for combining tolerances

Parameter	Tolerance	Sensitivity	Effect on merit function
x_1	σ_1	$\dfrac{\partial \Phi}{\partial x_1}$	$= \sigma_1 \cdot \dfrac{\partial \Phi}{\partial x_1}$
x_2	σ_2	$\dfrac{\partial \Phi}{\partial x_2}$	$= \sigma_2 \cdot \dfrac{\partial \Phi}{\partial x_2}$
x_3	σ_3	$\dfrac{\partial \Phi}{\partial x_3}$	$= \sigma_3 \cdot \dfrac{\partial \Phi}{\partial x_3}$
.	.	.	.
.	.	.	.
Root Sum Square			**= sqrt(sumsq(D1:D23))**

You can change the tolerance value

Sensitivities do not change

Automatically recalculate effect from each term and RSS

Example

From perturbation analysis

	value	tolerance	RMS spot rad	perturbation	RMS spot rad
Lens 1					
Radius 1 (mm)	622	0.2	0.000730	0.1	0.000365
Surface 1 (pow/irreg over TP)		.5 / .25	0.001089	.5 / .25	0.001089
thickness (mm)	45	0.1	0.000600	0.05	0.000300
Radius 2 (mm)	813	0.3	0.000743	0.1	0.000248
Surface 2 (waves/cm)		0.025	0.000757	0.025	0.000757
wedge(um)		50	0.000670	25	0.000335
tilt (um)		50	0.000245	50	0.000245
decenter (mm)		0.1	0.000300	0.1	0.000300

Tolerance

σ_i

Effect of tolerance

$$\Delta\Phi_i = \sqrt{\left(\Phi(x_i+\Delta x_i)\right)^2 - \Phi_0^2}\;\frac{\sigma_i}{\Delta x_i}$$

Perturbation

Δx_i

Effect of Perturb

$$\sqrt{\left(\Phi(x_i+\Delta x_i)\right)^2 - \Phi_0^2}$$

(+ many more terms, RSS at the end)

Tolerancing surface figure

- Specifications are based on measurement
  - Inspection with test plate.
    Typical spec: 0.5 fringe
  - 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 PSD spec
- 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

Assigning initial tolerances

- Start with rational, easy to achieve tolerances
- Only tighten these as your analysis requires
- Rules of thumb for element tolerances
- Rules of thumb for assembly tolerances

- ***Best -- know what the fabrication and alignment processes you plan to use will give!***

Using optical design codes

- Much of the above work can be done entirely within the optical design code.
- You can specify tolerances, and the software will calculate sensitivities and derive an RSS
- **Be careful with this!** It is easy to get this wrong.
- The optical design codes also include a useful Monte Carlo type tolerance analysis. This creates numerous simulations of your system with all of the degrees of freedom perturbed by random amounts.

Develop complete set of tolerances

- Start with tolerances that make sense
  - Use experience
  - Rules of thumb
- Check overall magnitudes of the terms
  - Terms with small effects, loosen tolerances
  - Terms with big effects, may need to tighten tolerances
- Revise fabrication, alignment plans as needed the goal is:

  1. **Meet performance specifications**
  2. **Minimize cost (or pain)**

Mechanical tolerancing

- This is a huge, important subject for opto-mechanical engineers.
- Basic types of tolerances for optical systems
  - General position tolerances
    - lens spacing and alignment
  - Surface texture
    - comes from fabrication process
  - Level of constraint
    - overconstrain for stiffness, clearance for motion
    - interference or clearance for optic mounts

Dimensional tolerances for machined parts

- Depends on fabrication methods and equipment so **discuss these with your fabricator!**
- Rules of thumb for machined parts
  - ± 1 mm for coarse dimensions that are not important
  - ± 0.25 mm for typical machining without difficulty
  - ± 0.025 mm precision machining, readily accessible
  - < ± 0.002 mm high-precision, requires special tooling

Fabrication of mechanical components

Most of the small (<1 m) parts for optics are made by cutting from oversized stock on a few common machines. These can be driven by a skilled operator, or by numerical control:

- Milling machine (aka “mill” or “Bridgeport”)
- Lathe
- Drill press

Other processes are used as needed:

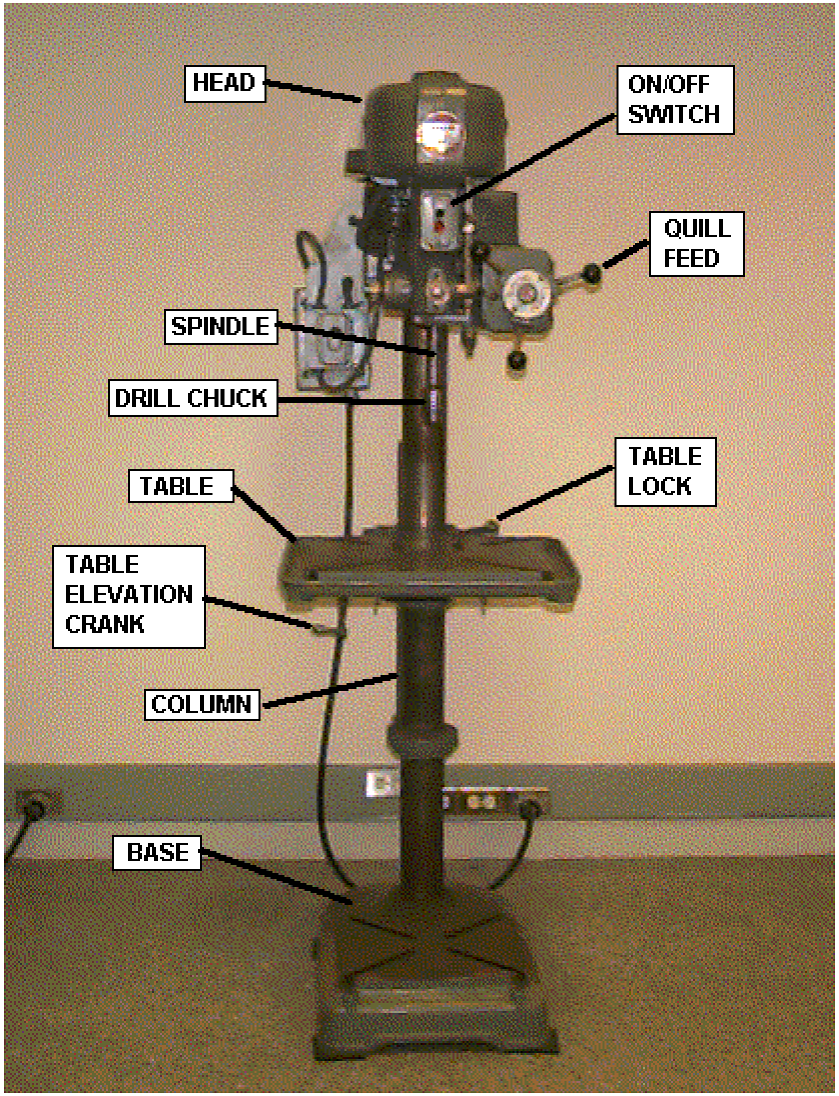
- Near net shape forming (Rolling, casting, extruding, stamping)
- Surfacing (bead blasting, grinding, lapping)
- Welding, brazing
- EDM (Electrical discharge machining)
- Precision cutting (Laser, abrasive water jet)

Different materials have very different limitations –
Get to know the guys in the shop

Drill Press

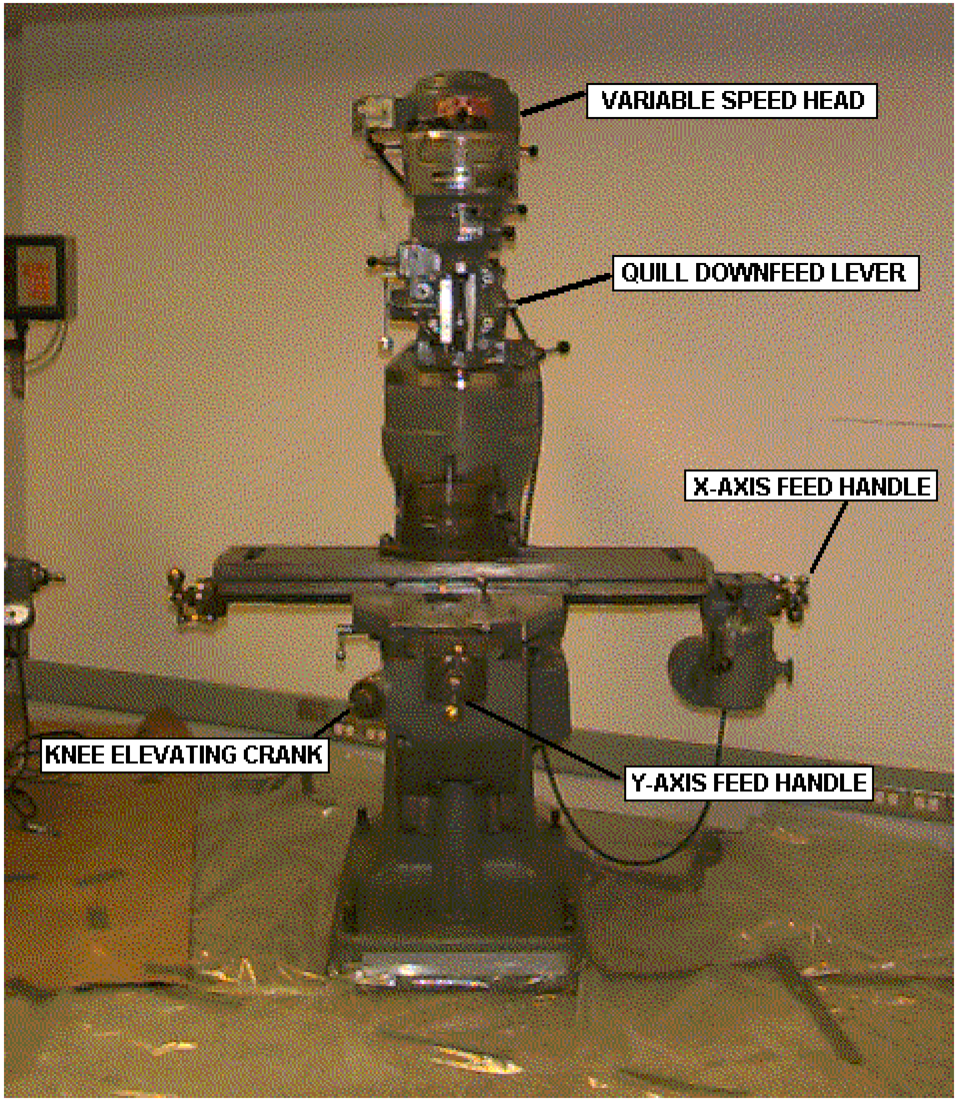
- Clamp part to table, drill holes one at a time
- Drilling, reaming and tapping

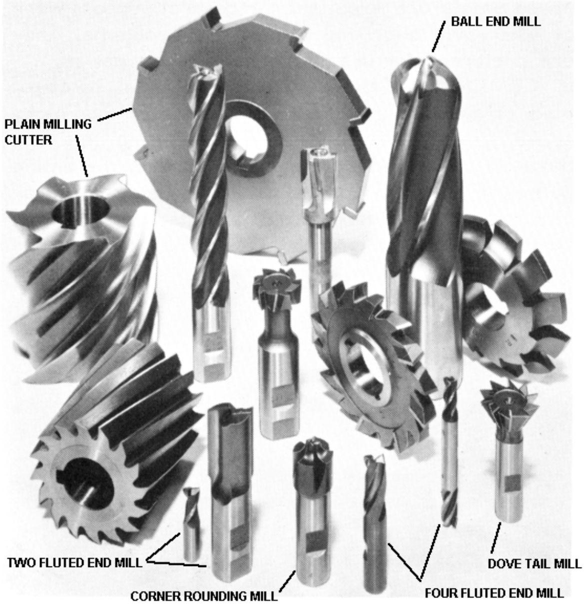
- Use center drill to locate holes to <0.005”.
- Holes drilled to 0.002” diam, reamed to <0.001” diam



Milling machine

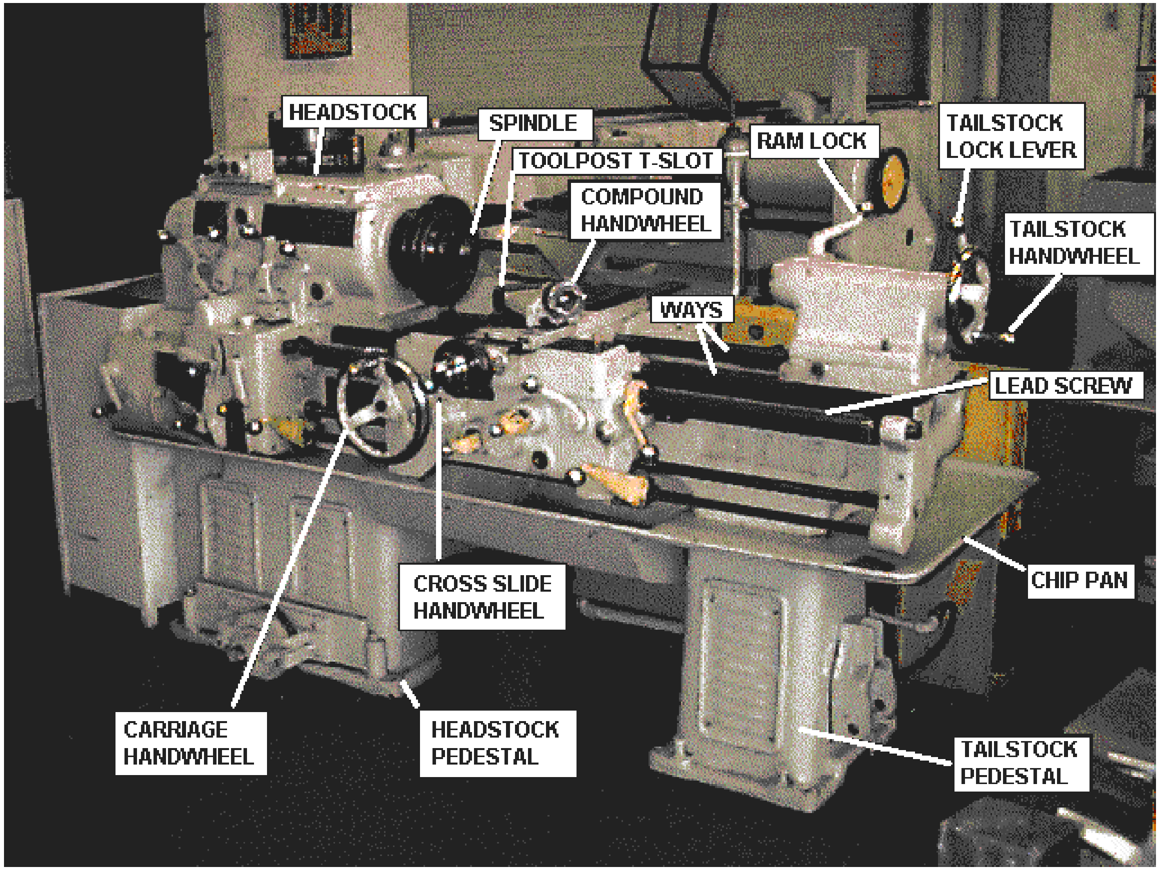
- Part is moved under rotating cutting tool
- Limitations:
  - Deformation of part to clamping
  - Backlash, stage limitations
  - Registration accuracy
  - Machine dynamics
  - Tool wear
- Accuracy
  - 0.005” accuracy is easy
  - < 0.001” is hard

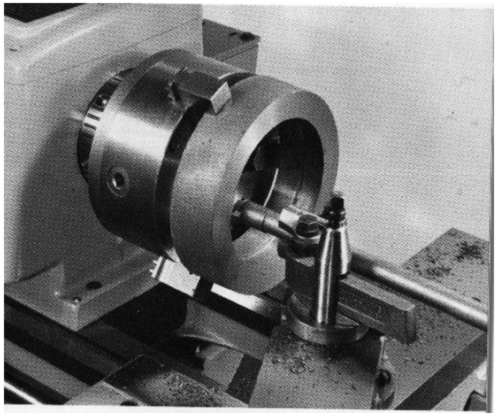




Lathe

- Part is rotated under tool
- Limitations:
  - Deformation of part to clamping
  - Backlash, stage limitations
  - Registration accuracy
  - Machine dynamics
  - Tool wear
- Accuracy
  - 0.005” accuracy is easy
  - < 0.001” is hard





Boring!

Numerically Controlled (NC) machines

- Very flexible, can make complex parts efficiently
- NC Mill, lathe, EDM
- Accuracy 0.002” is common, <0.0001” is possible
- Make complex parts, straight from the CAD output
- Well maintained machines produce excellent performance

Dimensional tolerancing of optical elements

- Diameter
- Clear aperture
- Thickness
- Wedge
- Angles
  - wedge or optical deviation for lenses
  - angles for prisms
- Bevels
- Mounting surfaces

Start with nominal tolerances from fabricator

Define assembly procedure

- Determine adjustments that will be made in assembly that can compensate other errors
  - Each of these needs a measurement to know how to set it
  - Consider several things --
    - Range of adjustment
    - Resolution required (for motion and for measurement)
    - Required accuracy of motion and measurement
    - Frequency of adjustment
- Other dimensions will be set once (like lenses in cells)

Tolerancing optical assemblies

- Element spacing
- Tilt of elements
- Mounting decenter
- Mounting distortion
- Include stability and thermal errors

Get nominal tolerances from assembly and alignment procedures

Work with the mechanical designer

Rules of thumb for optical assemblies

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 µ

<u>Base</u>: Typical, no cost impact for reducing tolerances beyond this.

<u>Precision</u>: Requires special attention, but easily achievable in most shops, may cost 25% more

<u>High precision</u>: Requires special equipment or personnel, may cost 100% more

Example – 2 element null corrector

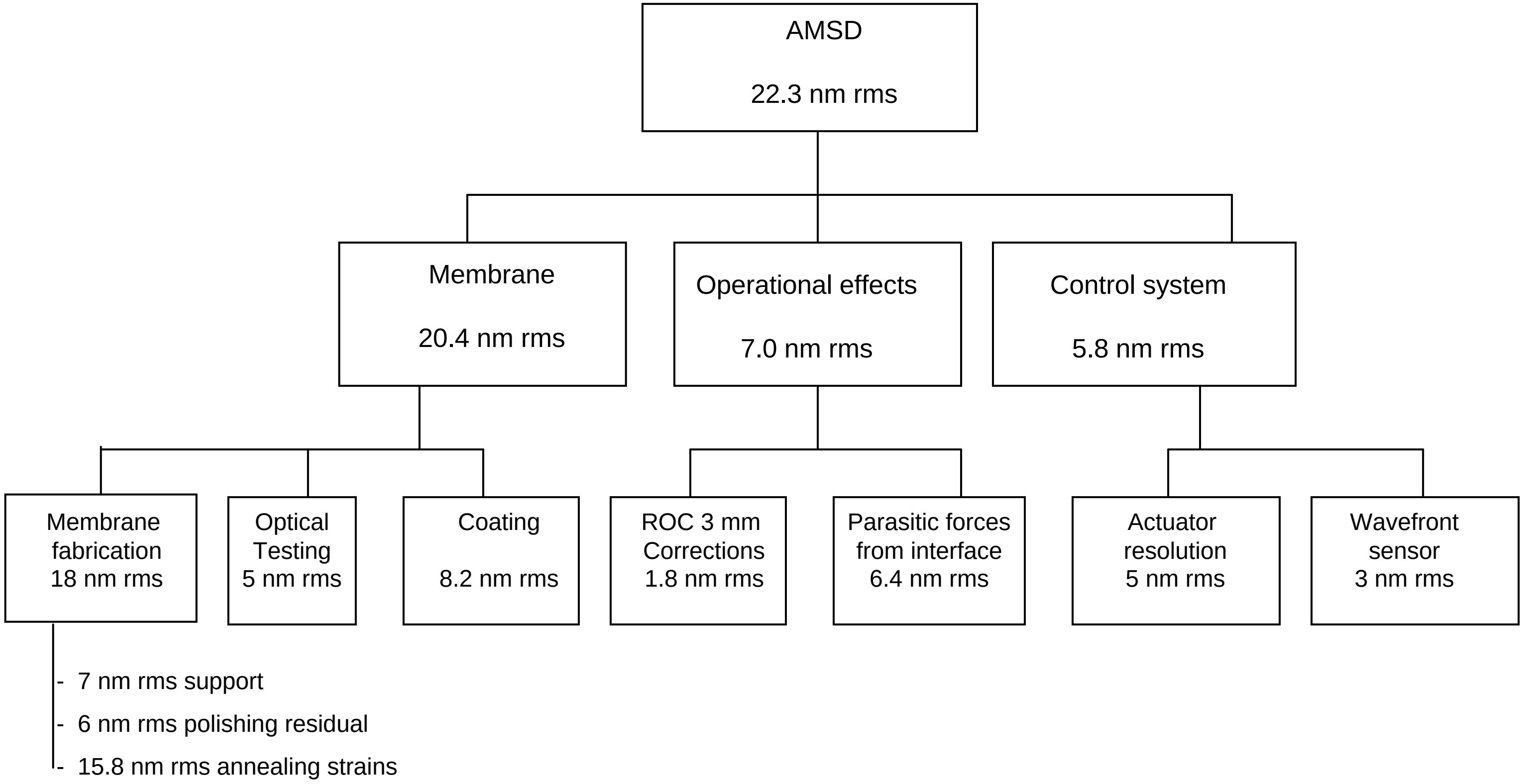
Table 3. Accuracy for null lens fabrication

Quantity	Tolerance
Lens spacing	50 µm
Lens thickness	25 or 50 µm
Radius of curvature	1 fringe power or 25 µm (whichever is smaller)
Flatness	$\lambda/4$
Surface figures	0.008 λ rms interferometer 0.015 λ rms lenses
Index of refraction	± 0.0002 (Grade A BK7)
Index Inhomogeneity	0.25 E-6 rms (H4 grade)
Wedge in lenses	50 µm
Decenter in mounting	50 µm
Tilt in mounting	50 µm
Primary radius of curvature	2 mm

Table 4. Tolerances for null lens

	units	Design value	uncertainty	Spherical aberration (nm rms)	Figure (nm rms)
Interferometer					
Irregularity (rms)	waves		0.008		5.06
Decenter	µm		0.050	0.00	0.03
Airspace	mm	103.972	0.05	1.36	0.00
Relay Lens:					
Curvature 1	/mm	0.00E+00	2E-06	0.22	0.02
Thickness	mm	10.386	0.025	0.47	0.02
Radius 2	mm	41.595	0.025	0.26	0.03
Irregularity 1 (rms)	waves		0.015		4.89
Irregularity 2 (rms)	waves		0.015		4.89
Index		1.51509	2E-04	1.17	0.02
Inhomogeneity	rms		2.5E-7		2.60
Wedge	µm		50	0.00	0.07
Decenter	µm		50	0.00	0.07
Tilt	µm		50	0.00	0.09
Airspace	mm	150.418	0.050	1.00	0.02
Field Lens:					
Radius 1	mm	129.681	0.050	0.88	0.04
Thickness	mm	2.924	0.050	0.01	0.02
Curvature 2	/mm	0.00E+00	1.4E-06	0.20	0.03
Irregularity 1 (rms)	waves		0.015		4.89
Irregularity 2 (rms)	waves		0.015		4.89
Index		1.51509	2E-04	0.89	0.03
Inhomogeneity	rms		2.5E-7		0.73
Wedge	µm		50	0.00	0.10
Decenter	µm		50	0.00	0.06
Tilt	µm		50	0.00	0.09
Residual Wavefront	waves		0.000182	0	0.06
Primary Radius	mm	7000	2	0.52	0.02
RSS				**3**	**11.34**

Error Tree



AMSD

22.3 nm rms

Membrane

20.4 nm rms

Operational effects

7.0 nm rms

Control system

5.8 nm rms

Membrane fabrication
18 nm rms

Optical Testing
5 nm rms

Coating

8.2 nm rms

ROC 3 mm Corrections
1.8 nm rms

Parasitic forces from interface
6.4 nm rms

Actuator resolution
5 nm rms

Wavefront sensor
3 nm rms

- 7 nm rms support
- 6 nm rms polishing residual
- 15.8 nm rms annealing strains

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