Introduction to Image Quality and Optical Elements

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OPTI-521 Presentation

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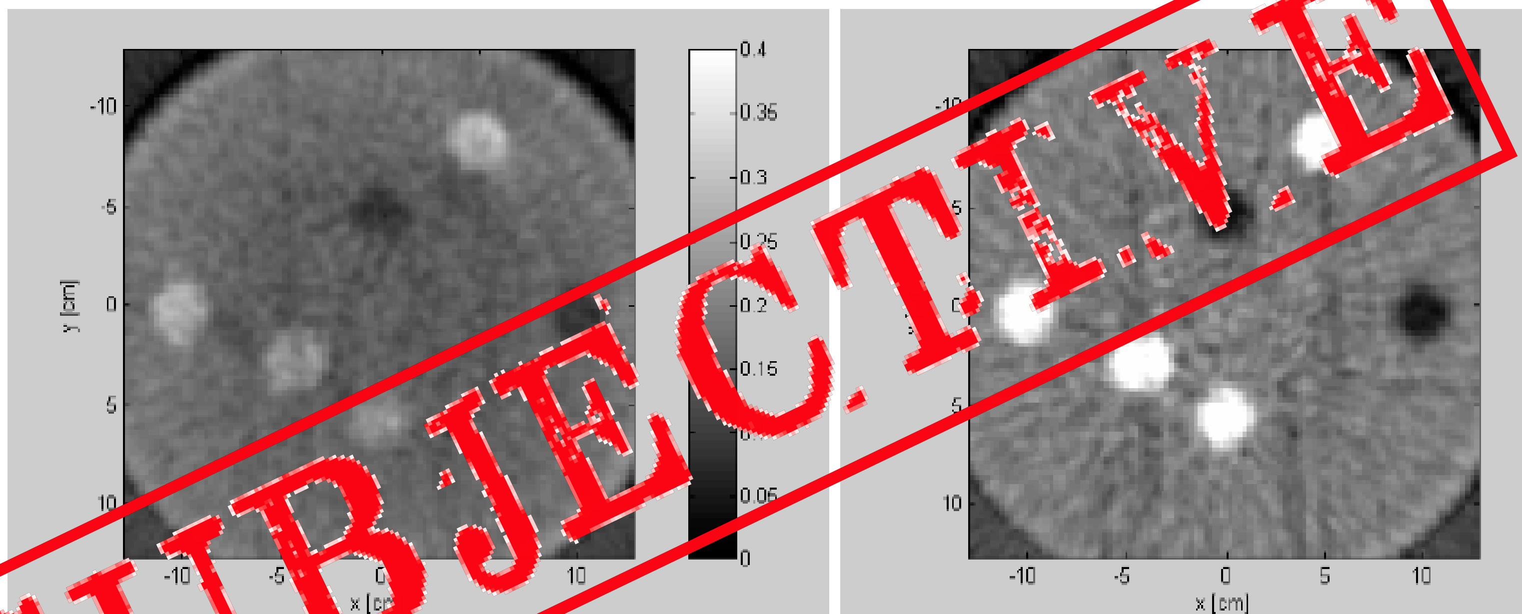
Outline

- Introduction: Image Quality
  - What it is? How do we define it? How can we measure it?
- The Imaging Equation
- The Point Spread Function and the OTF
  - Effect of Wavefront Error
- Sources of Wavefront Error
- Consequences and Conclusions

What is Image Quality?

- “I know it when I see it!” -Potter Stewart



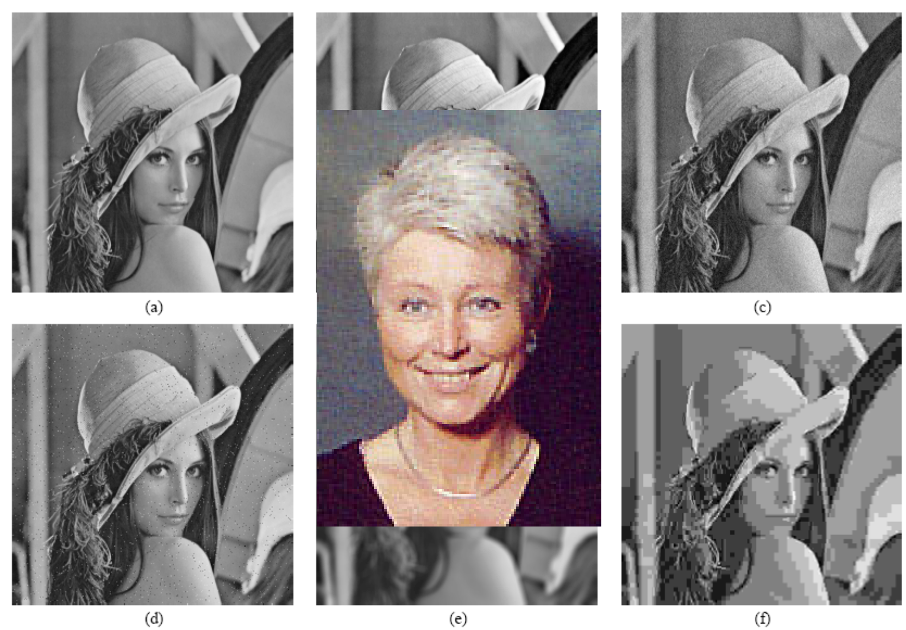
“These corrections ... improve drastically the image quality.”

Anon

Credit: Dr. Barrett’s OPTI-536 Slides

Something less subjective

- MSE (mean-squared error)
  - No relation to object information
  - Insensitive to small features
  - Sensitive to irrelevant features (magnification, color mapping)



Z. Wang et al.

ICASSP, 2002

Something else less subjective

- SNR or CNR (signal/noise , contrast/noise)

“The contrast-to-noise ratio CNR was used to determine the detectability of objects within reconstructed images from diffuse near-infrared tomography.”

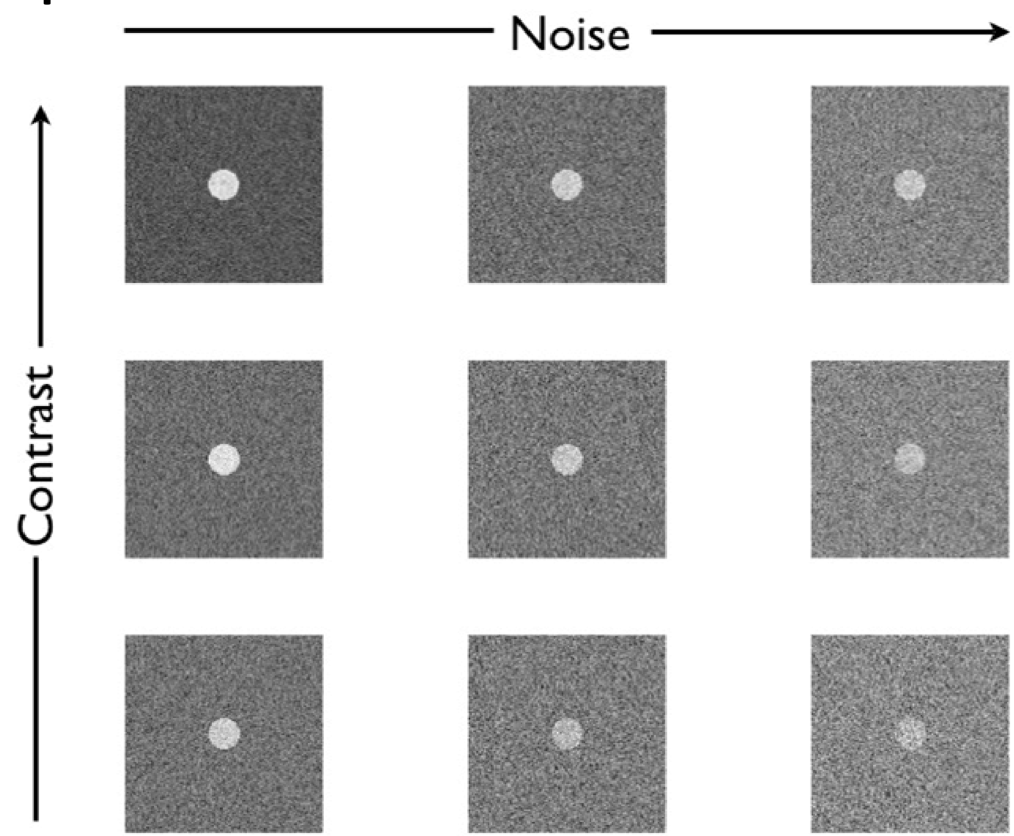
“... a CNR of 4 is required for detection of the object.”

“The CNR is a measurement of how well a region
of interest can be separated from surrounding regions ...”

“Higher field strengths are desirable for high-resolution imaging
because the signal-to-noise ratio (SNR) is proportional to field strength, and the detected signal is proportional to the tissue volume within a voxel. A reduction in voxel size from 1 × 1 × 1 mm to 0.1 × 0.1 × 0.1 mm therefore results in a 1000-fold *reduction* in the detected signal.”

CNR cont.

- Figure from Dr. Barrett's OPTI-536 Lecture
- Courtesy of Matt Kupinski
- Promising?



CNR cont.

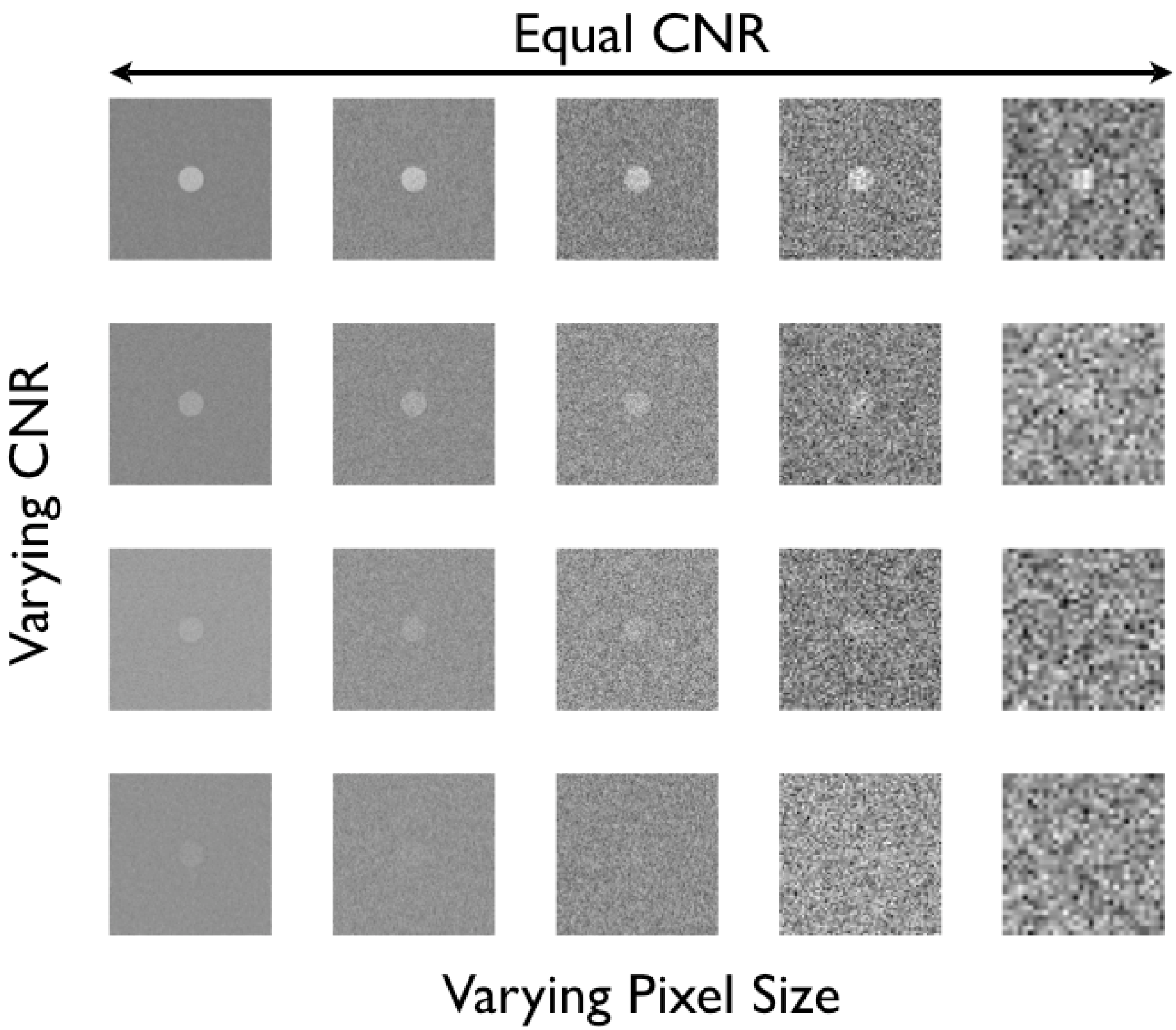
CNR

2.0

1.0

0.5

0.25



Task-based Image Quality

- What information is desired from the image?
- How will that information be extracted?
- What objects will be imaged?
- What measure of performance will be used?
  - Barrett and Meyers, "Foundations of Image Science"

What limits your ability to *extract information?*

The Imaging Equation

- g=Hf
  - Photography
    - f = discrete samples of an infinite series of points within object space
    - g = output pixel values
  - This convention lends itself naturally to the idea of a PSF (point spread function)
    - Consequence of diffraction
    - Ignoring geometrical aberration from here on out

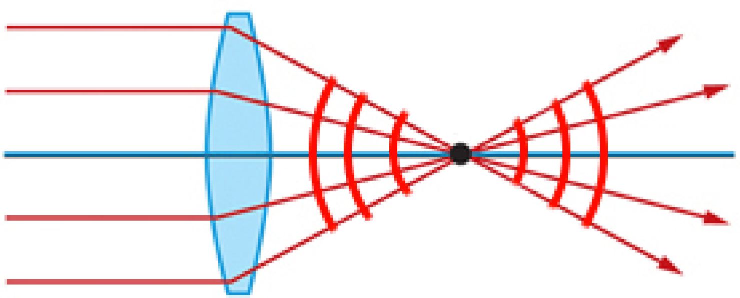
The Point Spread Function

- If the object is decomposed into a series of point objects, then the image may be considered as the object convolved with the system point spread function

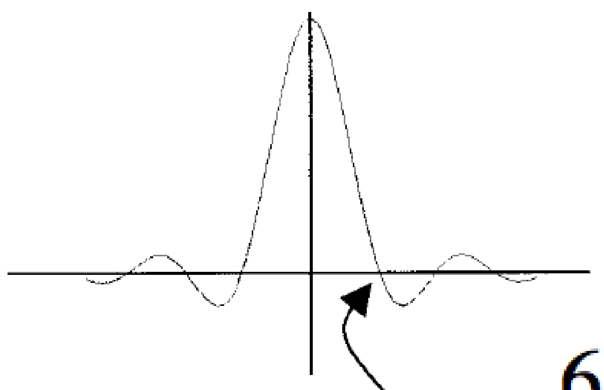
$$I_{im}^{(s)}(r) = I_{obj}(r) * p_{incoh}(r)$$

- Do a bunch of diffraction math to see that…

Diffraction Limited (Ideal) Imaging



$$t_{lens}(r) = e^{-ikR_f} t_{ap}(r)$$



$$r = \frac{.61\lambda}{NA'}$$

- In a well designed imaging system, the size of the diffraction-limited blur spot will correspond to the size of a detector element

- $D \cong f/\#_W$

Real Imaging

- Aberrations in the lens cause wavefront errors (phase), W(r)

$$t_{lens}(r) = e^{-ik\left(R_f - W(r)\right)} t_{ap}(r)$$

$$t_{pupil}(r) = t_{ap}(r) e^{ikW(r)}$$

$$\Rightarrow \quad p_{coh,ab}(\rho) = t_{pupil}\left(\frac{\lambda z'}{m}\rho\right) e^{ikW\left(\frac{\lambda z'}{m}\rho\right)}$$

The OTF/MTF

- Somewhat uglier math…
  - OTF (optical transfer function) describes contrast reduction of sine frequencies

$$\mathcal{H}(\rho) = \frac{\int_{-\infty}^{\infty} t_{pupil}\left(r + \frac{\lambda z'}{2m}\rho\right) t_{pupil}\left(r - \frac{\lambda z'}{2m}\rho\right) e^{ik\left[W\left(r+\frac{\lambda z'}{2m}\rho\right) - W\left(r-\frac{\lambda z'}{2m}\rho\right)\right]} dr}{\int_{-\infty}^{\infty} t_{pupil}(r)\, dr}$$

  - MTF is the modulus of the OTF, represents ratio of output modulation to input modulation

OTF/MTF Cutoff

- The maximum frequency that an imaging system will pass is:
  - Coherent: NA/λ
  - Incoherent: 2NA/λ

- Caution: Detectors have their own maximum frequency (Nyquist sampling, determined by pixel size) and if your optical MTF extends beyond this frequency, you will have aliasing

Quick note: aberration polynomials

- The OPD polynomial is one exponent higher than the transverse ray aberrations.
  - Third-order spherical aberration affects the wavefront proportional to the fourth power of the aperture
  - Third-order astigmatism is linear with aperture, and so the effect to the wavefront is quadratic with aperture
  - etc.

Sources of WFE

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

- Surface curvature
  - How closely does the optic match a test surface?
  - Count fringes (must specify λ)
  - Each bright-to-dark ring is $W_{PV} = \lambda/4$
- Figure error
  - The magnitude of small-scale surface irregularities
  - $W_{PV} = (n-1)N/2$
    - N is # of fringes of irregularity

Other sources of WFE

- Index inhomogeneity
  - $W_{PV} = \delta n \frac{t}{\lambda}$ ⍰ $\delta n \approx \pm 10^{-4}$
- Temperature, Vibration, Deformation
  - No great RoT, use FEA (we can do that!)

W_{PV}/W_{RMS}

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

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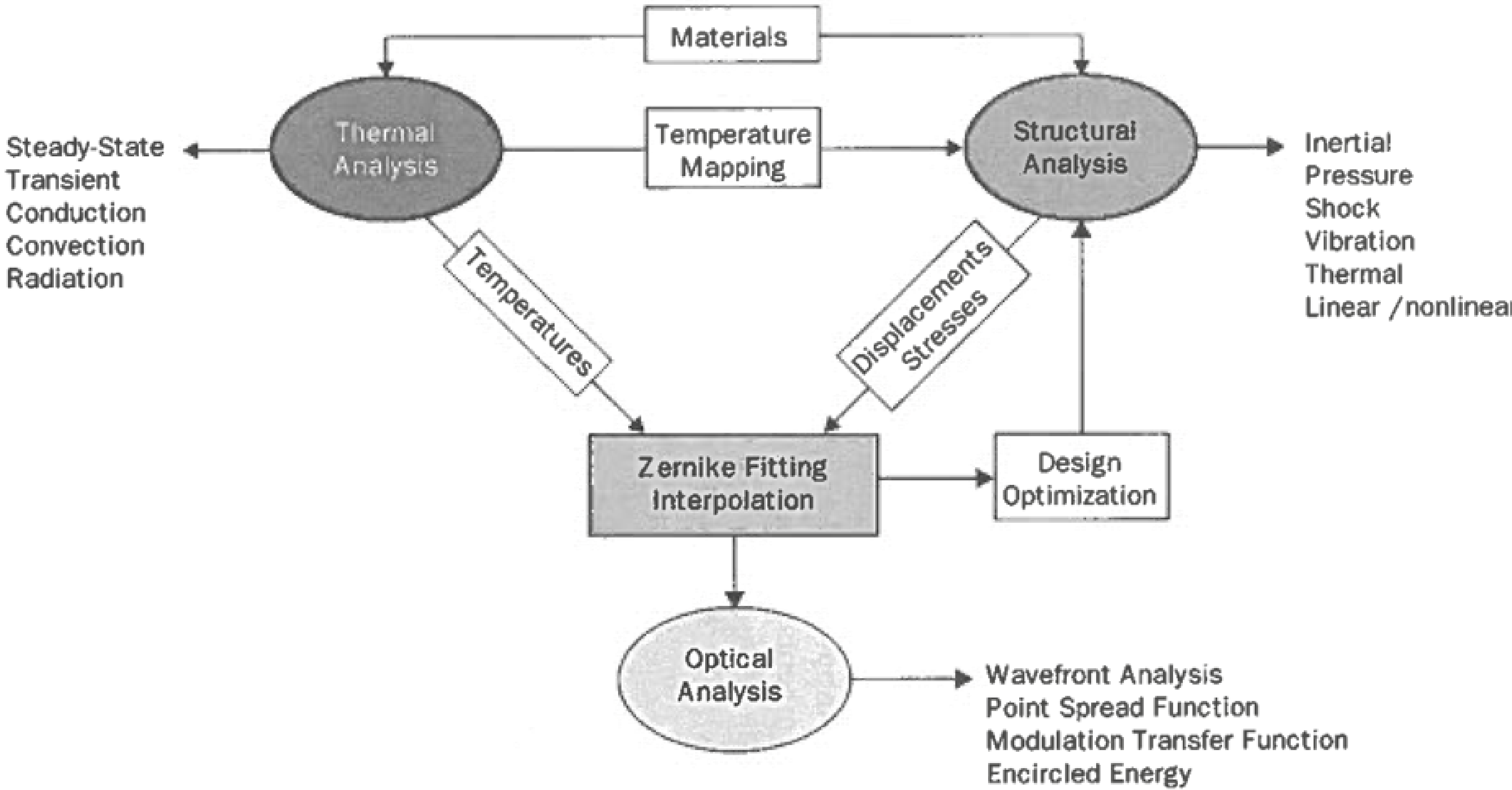
Wavefront Aberration	W_{PV}/W_{RMS}
Defocus	3.5
Spherical	13.4
Coma	8.6
Astigmatism	5
Random Fabrication Errors	*5*

  - In a complex system, each lens should have on the order of λ/10 waves P-V error.

Conclusions: The Big Picture

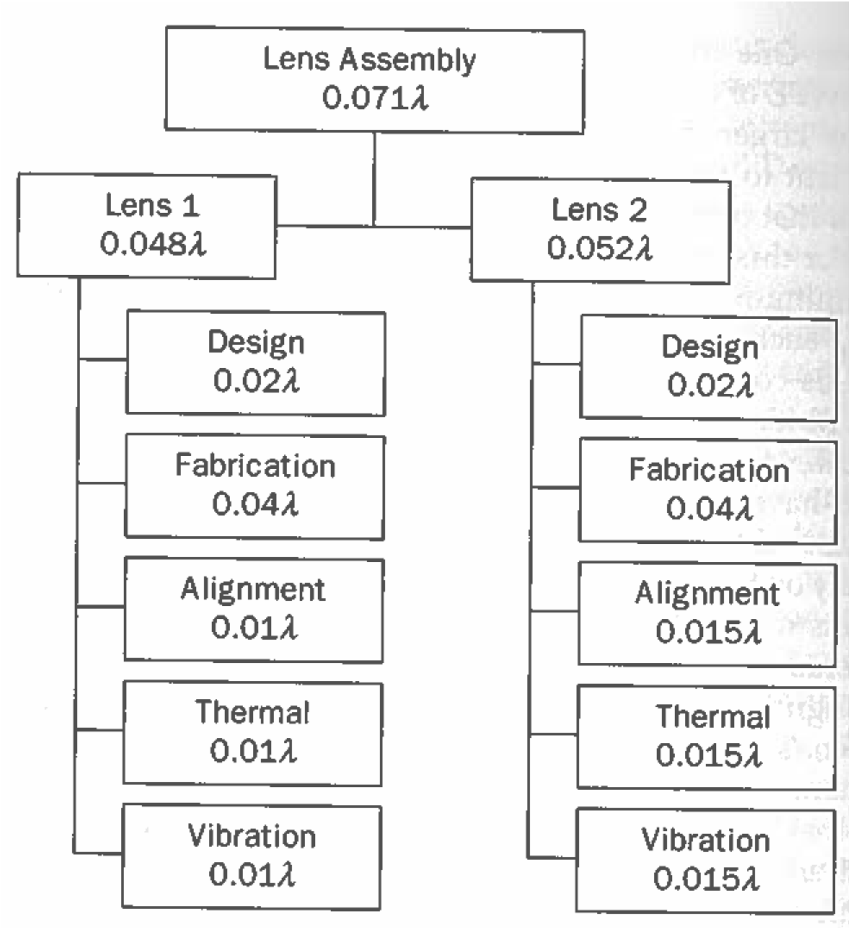


Credit: Sigmadyne

Conclusions: The Little Picture

- Detector pixel size determines ideal f/#
  - Both for spot size and to avoid aliasing
- Rayleigh criterion says to keep $W_{PV} < \lambda/4$
  - Have more complex forms relating WFE to PSF and OTF if we need them
- This allowable WFE must be allocated, and we have several good sources for determining cost and feasibility of tolerancing

Example RMSWFE Budget



Credit: Keith Kasunic,
Optical Systems Engineering

Questions?

Misc. References/Resources:

OPTI-536 Course Slides – Dr. Harry Barrett
Foundations of Image Science, Barrett and Meyers
Optical System Design, Robert E. Fisher
Optical Systems Engineering, Keith J. Kasunic