LIGHT BUCKET ASTRONOMY

Aberration Theory and Prototype Mirror Experiments

Bruce Holenstein, Rich Mitchell, Dylan Holenstein

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Agenda

- Some Light Bucket Aberration Theory
- Gravic Labs Pneumatic Mirror Prototypes
- Early Starstone Evaluation
- Other Mirrors

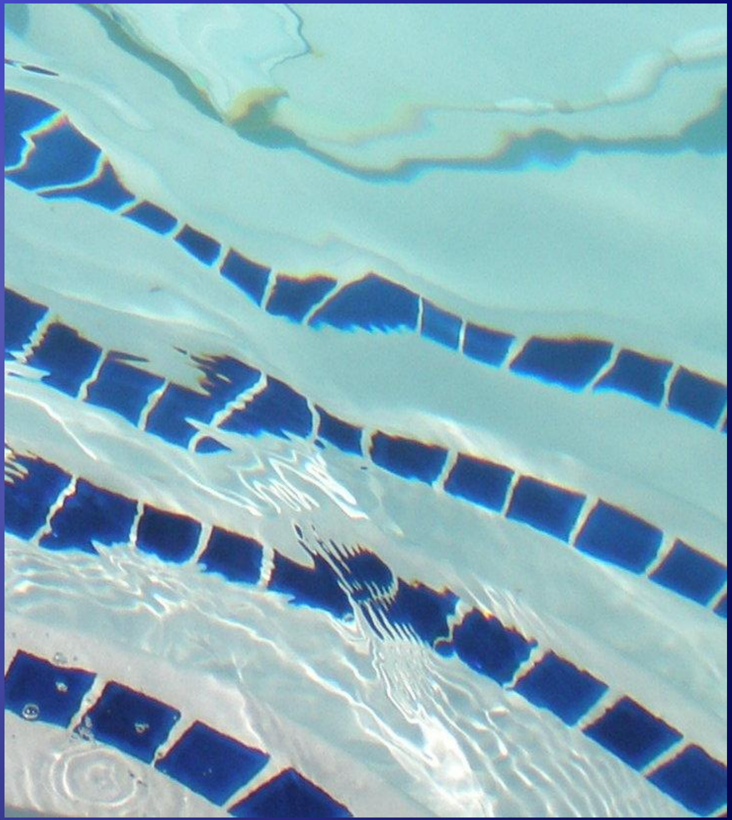
Background & Motivation I

- Pneumatic mirrors for astronomy
  - Study started in 1991 at the U. of Pennsylvania and continued there through 1998
  - Resurrected at Gravic in 2008 for ground-based light buckets
  - Science interests – Intensity interferometry, occultations, high speed aperture photometry

Gravic 42" on IPI393 GEM

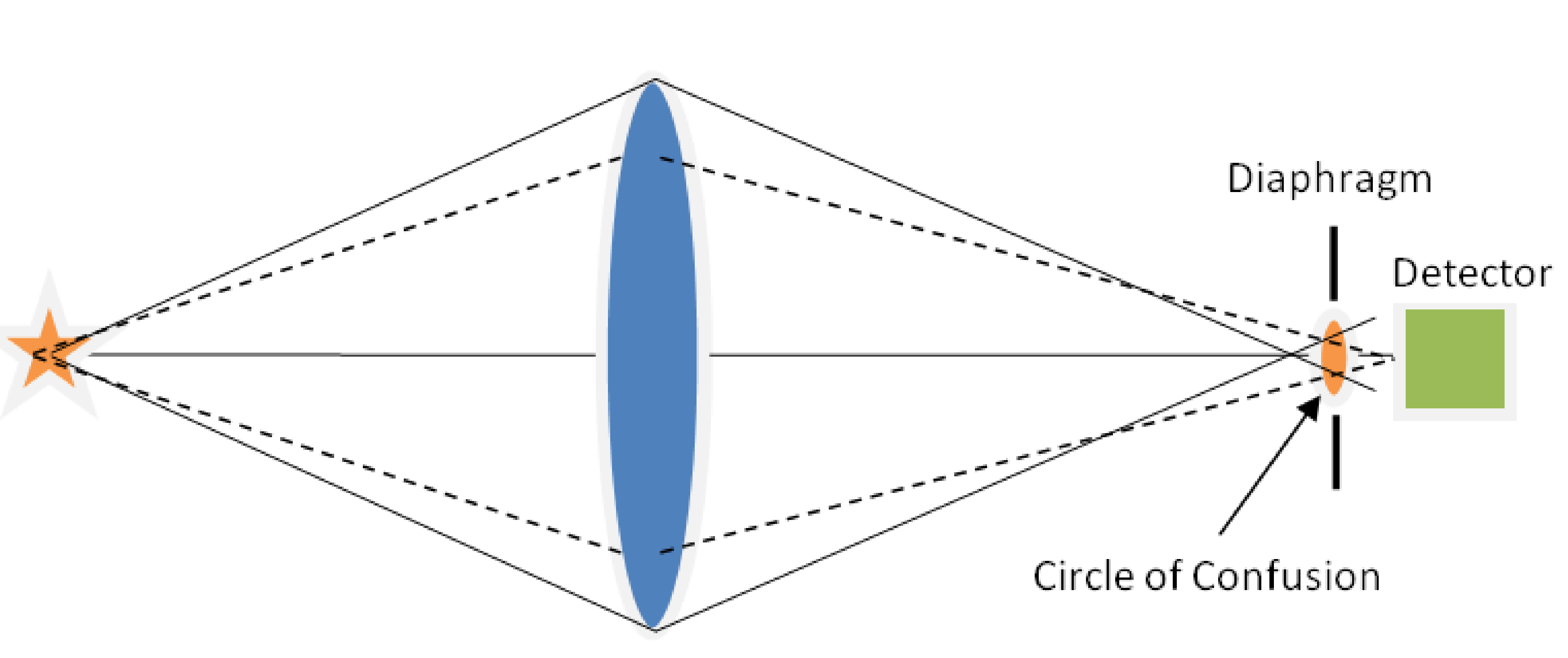
Background & Motivation II

- Tools were needed to characterize progress and failure in our work
  - Traditional quantification such as P-V and Strehl Ratio were not helpful
  - "Highly aberrated" to us signifies many waves of caustic, ray-crossing aberrations



Pool caustics

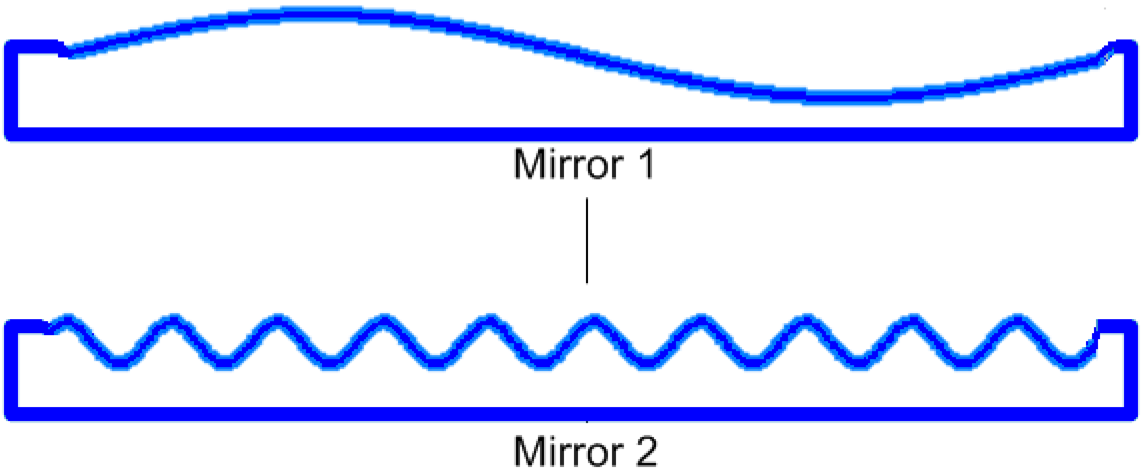
Circle of Confusion



- Circle of Confusion = blur spot at focal plane
- Diaphragm = circular isolator before the detector

Aberration Characterization I

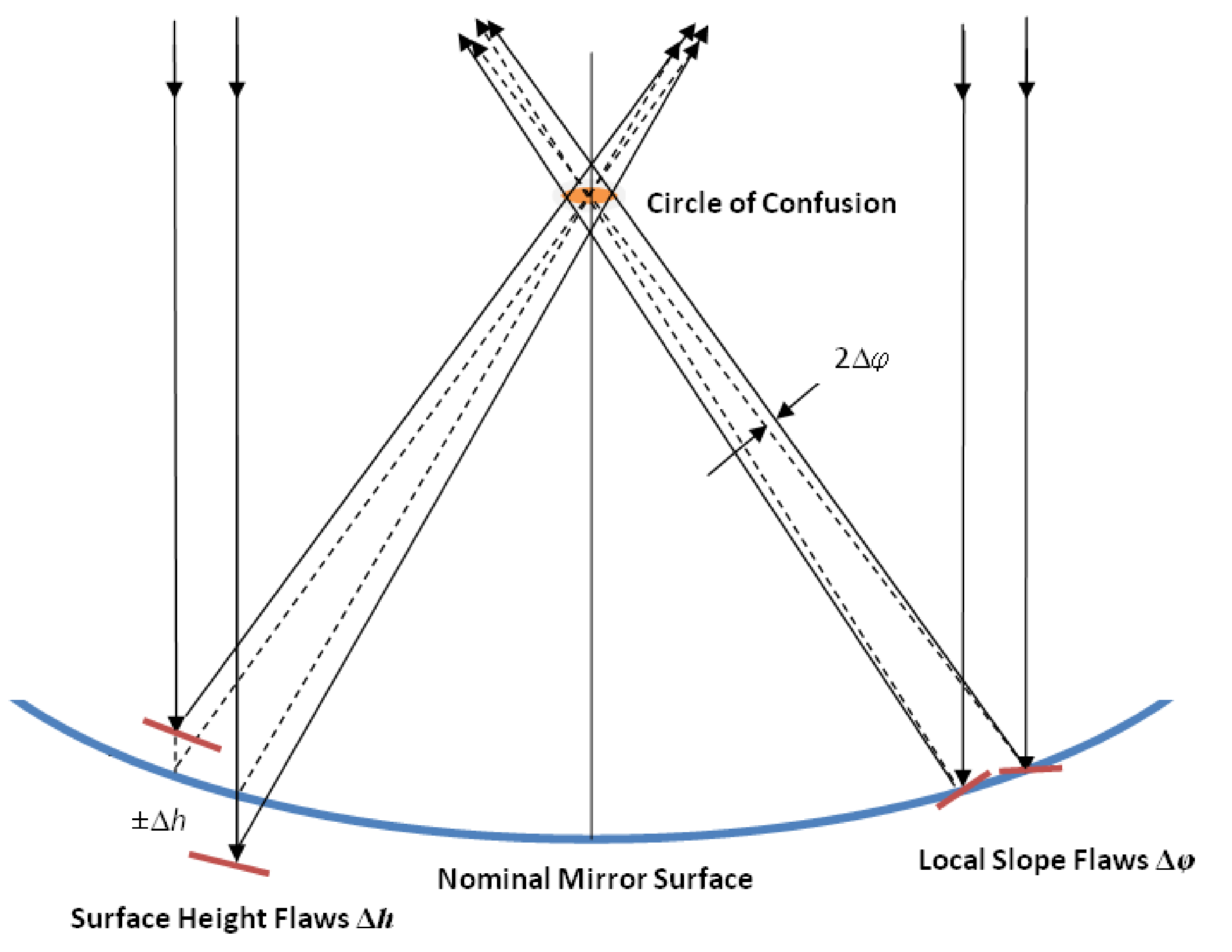
- P-V and Strehl Ratio are the same in the figure
- But, the RMS local slope gradient is very different



P-V and RMS measures are the same for both mirrors!
But, not $|\Delta\varphi|_{rms}$ (rms slope)

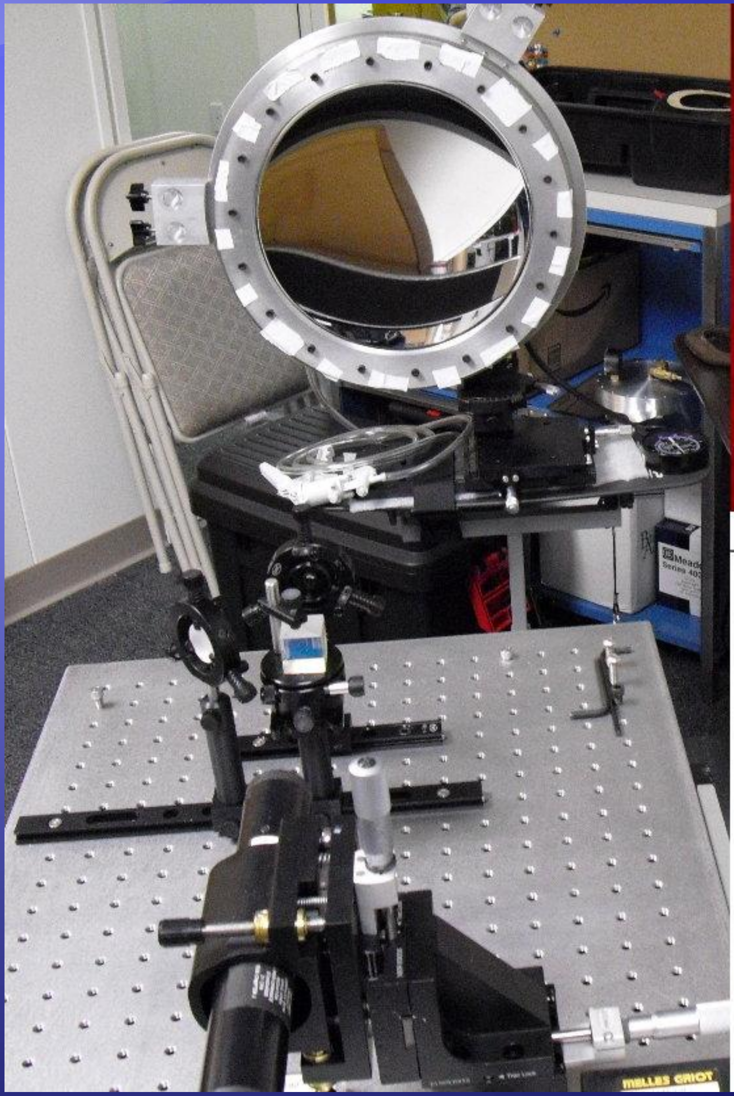
Aberration Characterization II

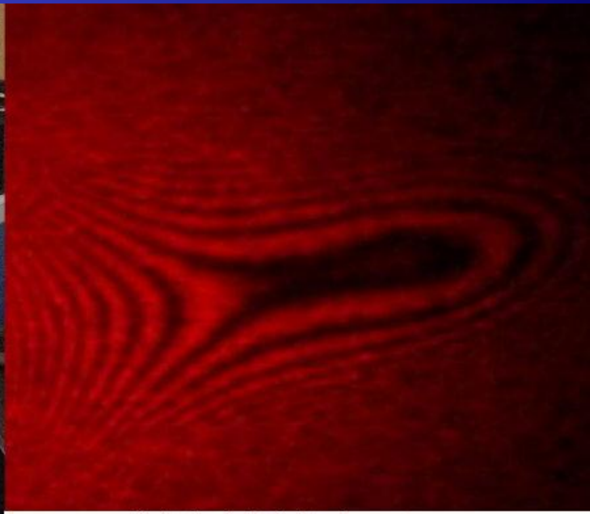
- Two aberration types considered analytically
  - Random surface height variations
  - Random local slope problems

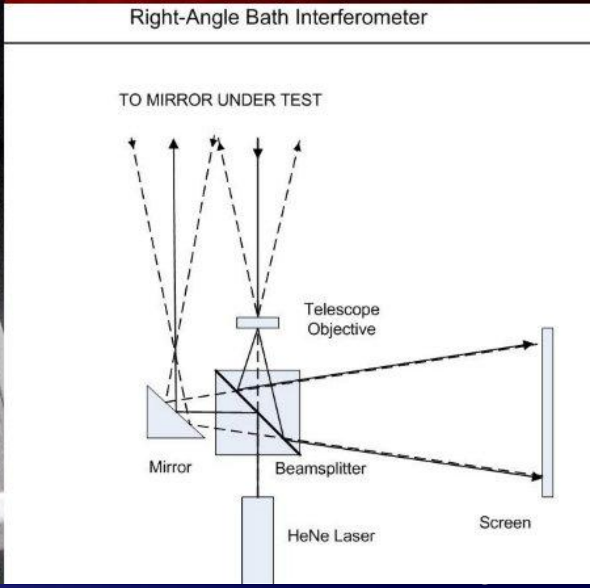


Aberration Characterization III

- Zone-sampling with a Right-angle Bath Interferometer
- Analysis produces Zernike representation of wavefront , $W(\rho,\theta)$
- Stitching and statistical combination of sample zone results







Aberration Characterization IV

- Diameter of CoC from surface height flaws:

$$d_{CoC,surface\ height}(n) \approx 0.5 n\sigma / f$$

- Diameter of CoC from local slope flaws:

$$d_{CoC,local\ slope}(n') \approx 4n'F\ |\Delta\phi|_{rms}$$

where *f* is the focal ratio, *F* is the focal length, and the *n and n'* multipliers determine the encircled flux fraction

Aberration Characterization V

- Zernike wavefront representation, $W(\rho,\theta)$, is used for the estimation of $\boldsymbol{\sigma}$ and $|\Delta\varphi|_{rms}$
- 1 $$W(\rho,\theta) = \sum_j a_j Z_j(\rho,\theta)$$
- 2 $$\sigma_W^2 = \langle W^2(\rho,\theta)\rangle - \langle W(\rho,\theta)\rangle^2 = \sum_{i=2} a_j^2$$
- 3 $$\nabla W(\rho,\theta) = \frac{\delta W}{\delta \rho}\,\boldsymbol{e_\rho} + \frac{1}{\rho}\frac{\delta W}{\delta \theta}\,\boldsymbol{e_\theta}$$
- 4 $$|\Delta\phi|_{rms} = \frac{\|\nabla W\|_{rms}}{D/2}$$

Aberration Characterization VI

- Calculation of the rms wavefront gradient norm from Zernike coefficients (Southwell 1982, Braat 1987)

$$\langle \|\nabla W\|^2 \rangle = \sum_{l=1}^{\infty} 8l \left[\sum_{i=l}^{\infty} \sqrt{2i+1}\, a_{2i}^{0} \right]^2 + \\ + \sum_{m=1}^{\infty} \left\{ m \left[\sum_{i=0}^{\infty} \sqrt{2(2i+m+1)}\, a_{2i+m}^{m} \right]^2 + \\ + \sum_{l=1}^{\infty} 2(2l+m) \left[\sum_{i=l}^{\infty} \sqrt{2(2i+m+1)}\, a_{2i+m}^{m} \right]^2 \right\}$$

- *FringeXP* (Rowe 2003) coefficient form

$$\|\nabla W\|_{rms} \approx \left[Z_1^2 + 2Z_1Z_6 + Z_2^2 + 2Z_2Z_7 + 8Z_3^2 + 16Z_3Z_8 + 2Z_4^2 + 2Z_5^2 + 7Z_6^2 + 7Z_7^2 + \\ + 24Z_8^2 + 3Z_9^2 + 3Z_{10}^2\right]^{\frac{1}{2}} .$$

Southwell, W. H. 1982, *Proc. SPIE*, **365**, pp. 97-104

Braat, J. 1987, *J. Opt. Soc. Am.*, **A4**, pp. 643-650

Aberration Characterization VII

- How much aberration is permissible?

For surface height flaws, the **rms wavefront error** must not exceed

$$\sigma_{\mathrm{limit}} \approx 2 f \, d_{Diaphragm} / n$$

An *f*/2 mirror with 1.3-mm rms smooth surface height aberrations (*i.e.*, 2600 waves of 500-nm light) feeding a 1-mm diameter diaphragm encircles 99.7% of the flux (*n*=3).

Aberration Characterization VIII

For local slope flaws, the **rms wavefront gradient norm** must not exceed

$$\|\nabla W\|_{rms,limit} \approx \frac{d_{Diaphragm}}{8n'f}$$

An *f*/2 mirror with a 1-mm diaphragm tolerates 42-waves (500-nm) rms wavefront gradient norm aberration and still encircles 98.9% of the flux (n'=3).

Aberration Characterization IX

- Solving for the spot size gives a useful rule of thumb:

$$\text{FWHM spot size (arc sec)} = 2.35 \; x \; 2|\Delta\varphi|_{rms}$$
$$= 2.35 \; x \; 4\|\nabla W\|_{rms}/D \approx 10^6 \;\; E/D$$

where *E* is the "wavefront error," *D* is the mirror diameter in the same units.

e.g., 2 waves=10^{-6}-m on 1-m mirror ~ 2" FWHM

Note: *E* depends on the type of aberration (above holds for when rms grad norm = 0.5 (P-V), e.g., for tilt).

Common Aberration Gradients

Zernike Gradients

			"E"	RMS Wavefront Gradient	Ratio
j	**Type**	**Polynomial**	**P-V**	$\lVert \nabla W_j \rVert_{rms}$	RMS Grad/E
1	Piston	1	a_1	0	0
2	X Axis Tilt	$2\rho\ cos\theta$	$4a_2$	$2\ a_2$	0.5
3	Y Axis Tilt	$2\rho\ sin\theta$	$4a_3$	$2\ a_3$	0.5
4	Defocus (power)	$\sqrt{3}(2\rho^2 - 1)$	$2\sqrt{3}\ a_4$	$2\sqrt{6}\,a_4$	1.4
5	45° Astigmatism	$\sqrt{6}\rho^2\ sin2\theta$	$2\sqrt{6}\ a_5$	$2\sqrt{3}\ a_5$	0.7
6	0° Astigmatism	$\sqrt{6}\rho^2\ cos2\theta$	$2\sqrt{6}\ a_6$	$2\sqrt{3}\ a_6$	0.7
7	Y Coma	$2\sqrt{2}(3\rho^2 - 2\rho)sin\theta$	$\frac{16\sqrt{2}}{3} a_7$	$2\sqrt{14}\ a_7$	1.0
8	X Coma	$2\sqrt{2}(3\rho^2 - 2\rho)cos\theta$	$\frac{16\sqrt{2}}{3} a_8$	$2\sqrt{14}\ a_8$	1.0
9	30° Trefoil	$2\sqrt{2}\rho^3\ sin3\theta$	$4\sqrt{2}\ a_9$	$4\sqrt{6}\ a_9$	1.7
10	0° Trefoil	$2\sqrt{2}\rho^3\ cos3\theta$	$4\sqrt{2}\ a_{10}$	$4\sqrt{6}\,a_{10}$	1.7
11	Principal Spherical	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$	$\frac{3\sqrt{5}}{2} a_{11}$	$2\sqrt{30}\ a_{11}$	3.2

Note: Malacara (2007) normalization

Figures of Merit I

- How do aberrations affect the Signal-to-Noise-Ratio (SNR)?

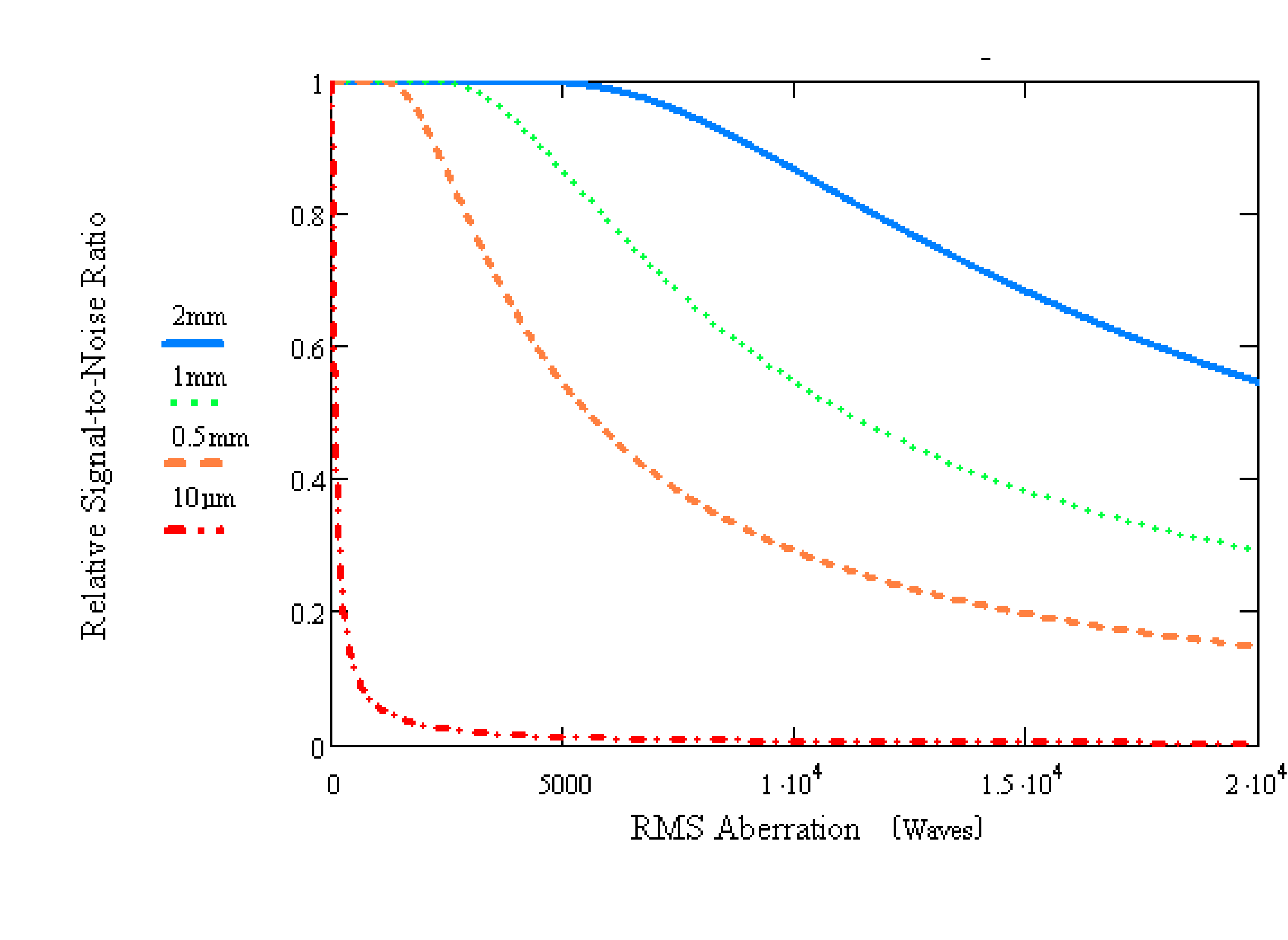
$$SNR = \frac{N_{Star+Sky} - N_{Sky}}{\sqrt{N_{Star+Sky} + N_{Sky} + N_{Detector} + S^2}}$$

where *Ns* are counts and *S* models atmospheric scintillation

- Figures of merit follow for various mirror situations

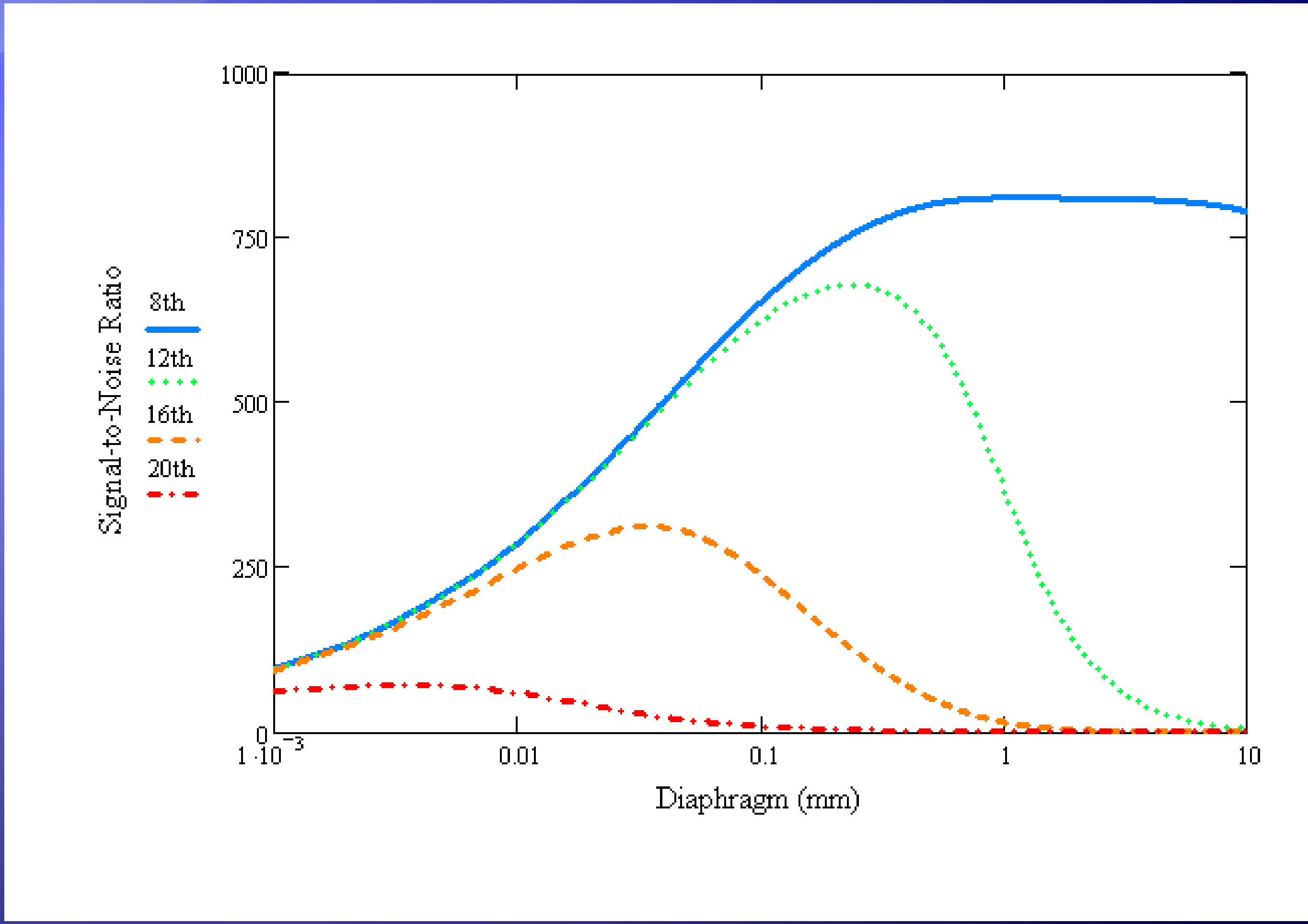
Figures of Merit II

- Random surface height aberrations
- Bright point source
- *f*/1.9, 1.6-m mirror
- Various diaphragms
- Visible light

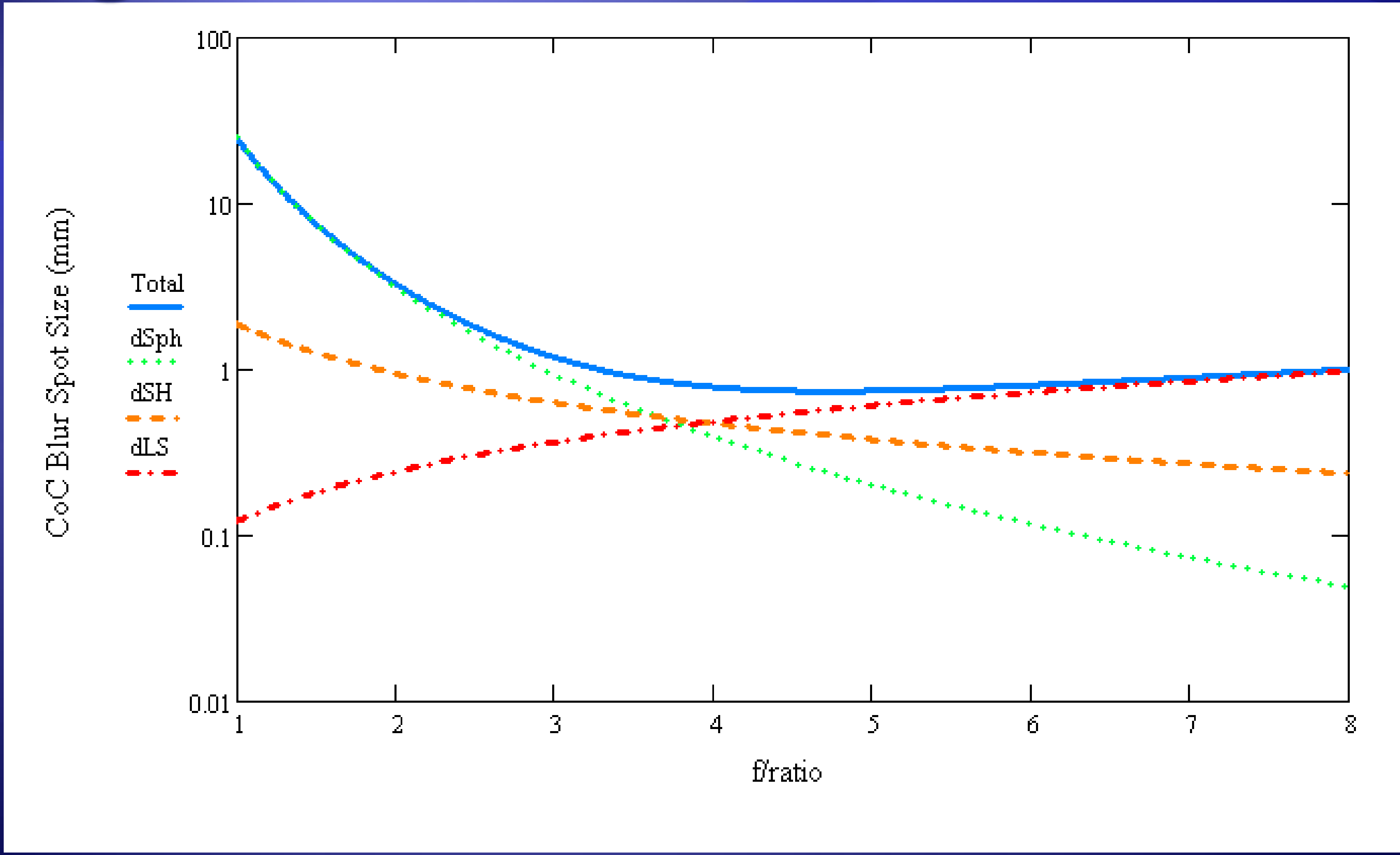


Figures of Merit III

- Local slope aberrations : 10 waves rms gradient norm
- 4 program star cases; *V* = +21 / arcsec squared background
- *f*/1.9, 1.6-m mirror
- Scintillation 1000-m, air-mass 1.5



Figures of Merit IV



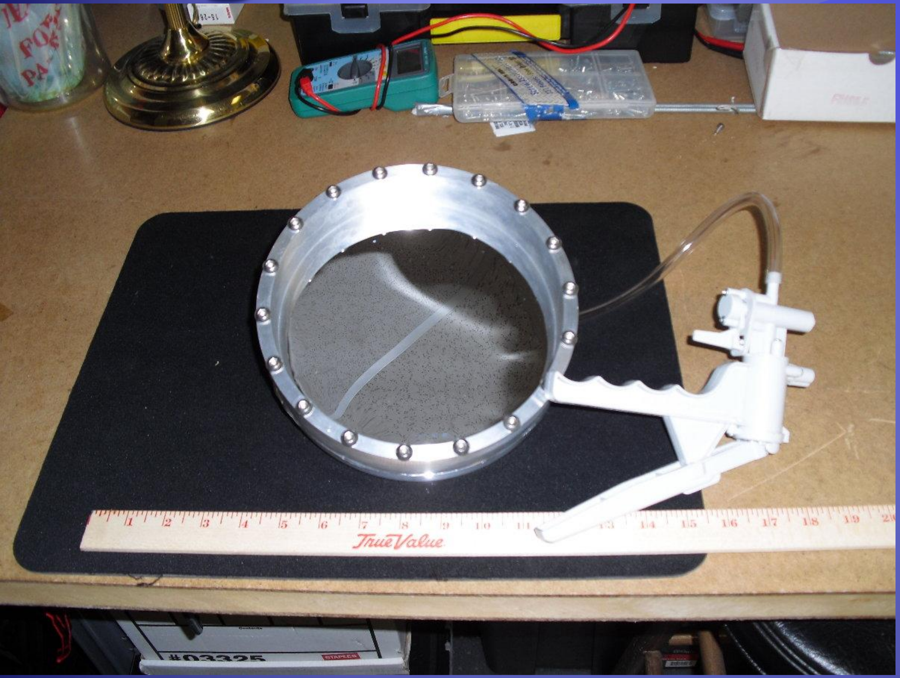
CoC size as a function of *f-ratio*. Spherical, 2500 waves rms surface height, and 10 waves rms gradient norm local slope aberrations are depicted.

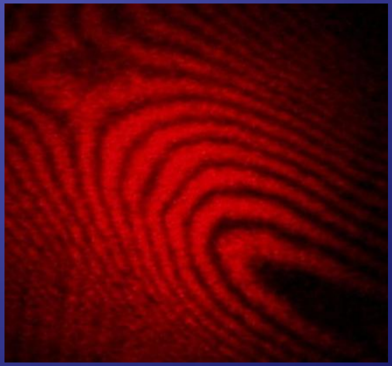
Light Bucket Mirror Conclusions

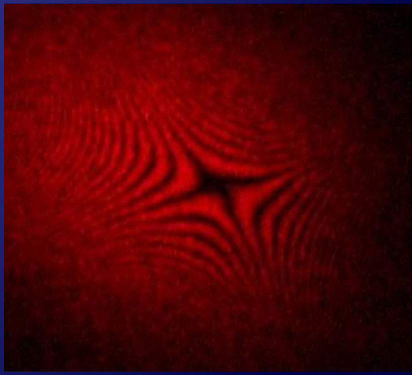
We used a statistical approach for light bucket mirror quality analysis: rms local surface height and wavefront gradient norm values. Some conclusions:

- When possible, limit the diaphragm size to improve the SNR, but not so much as to cause significant tracking errors
- For faint objects peak SNR occurs when diaphragms smaller than the size needed to collect 99% of the flux are used
- Light bucket mirrors excel if the program object is bright in comparison to the background

Light Bucket Mirror Prototype



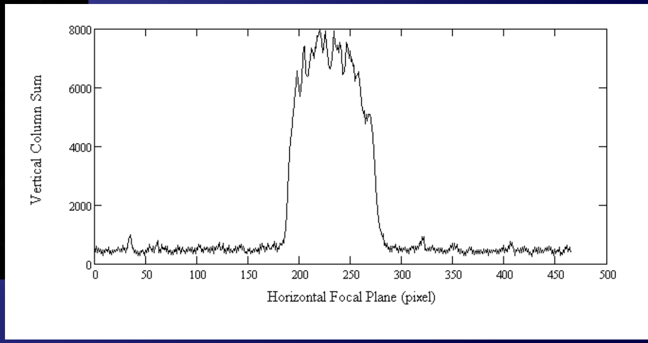




- 7” pneumatic mirror
- Complex interferograms

Light Bucket Mirror Prototype II

- 12" pneumatic mirror
- Vega (w/no correction)



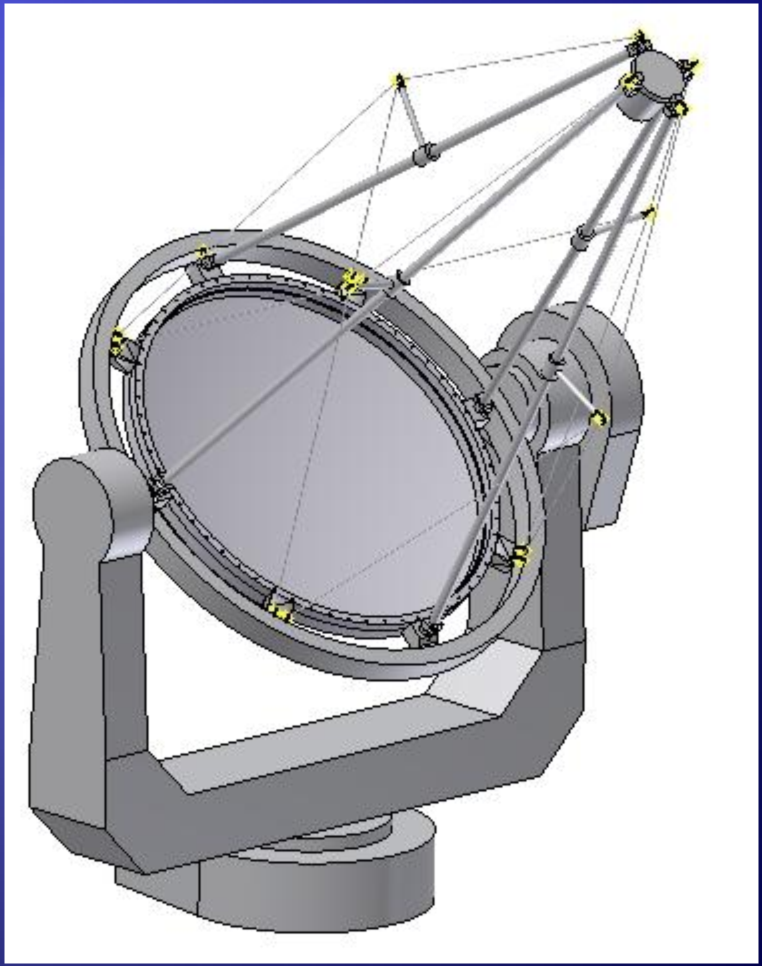
Vega 5-um/pixel

Light Bucket Mirror Prototype III

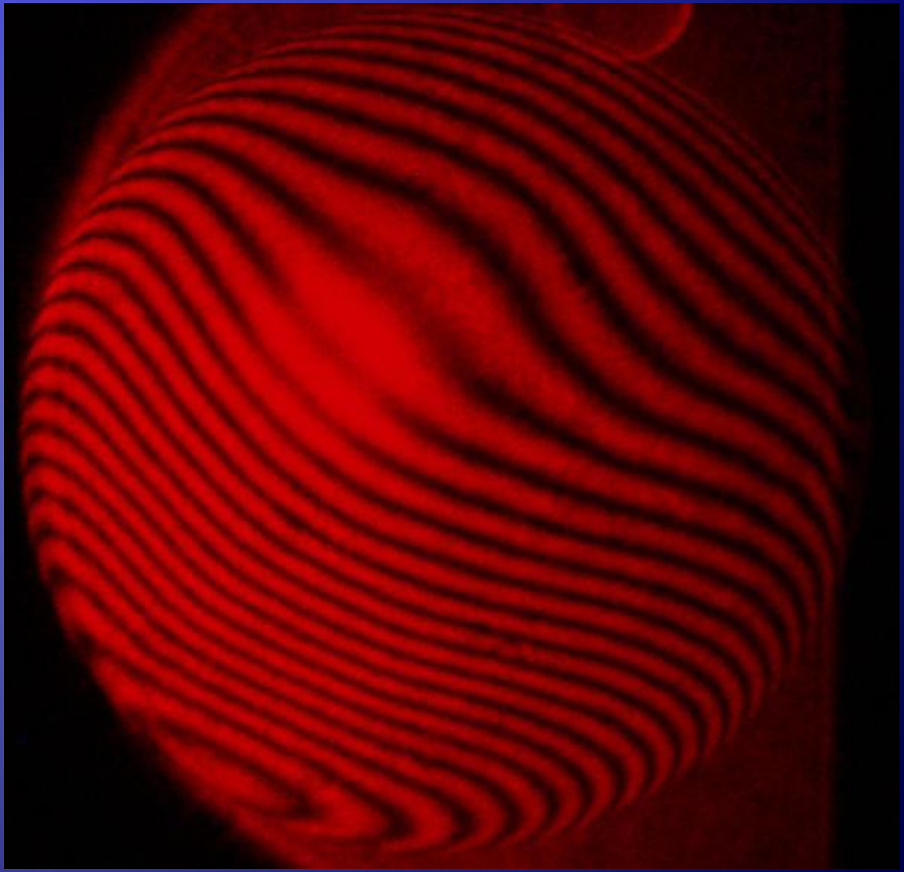
- Our first 1-meter light bucket at Gravic…

Light Bucket Mirror Prototype IV

- 1.6-m mirror scope design
  - Forged AL mirror cell
  - Plans on hold pending better mirror substrates and portable designs

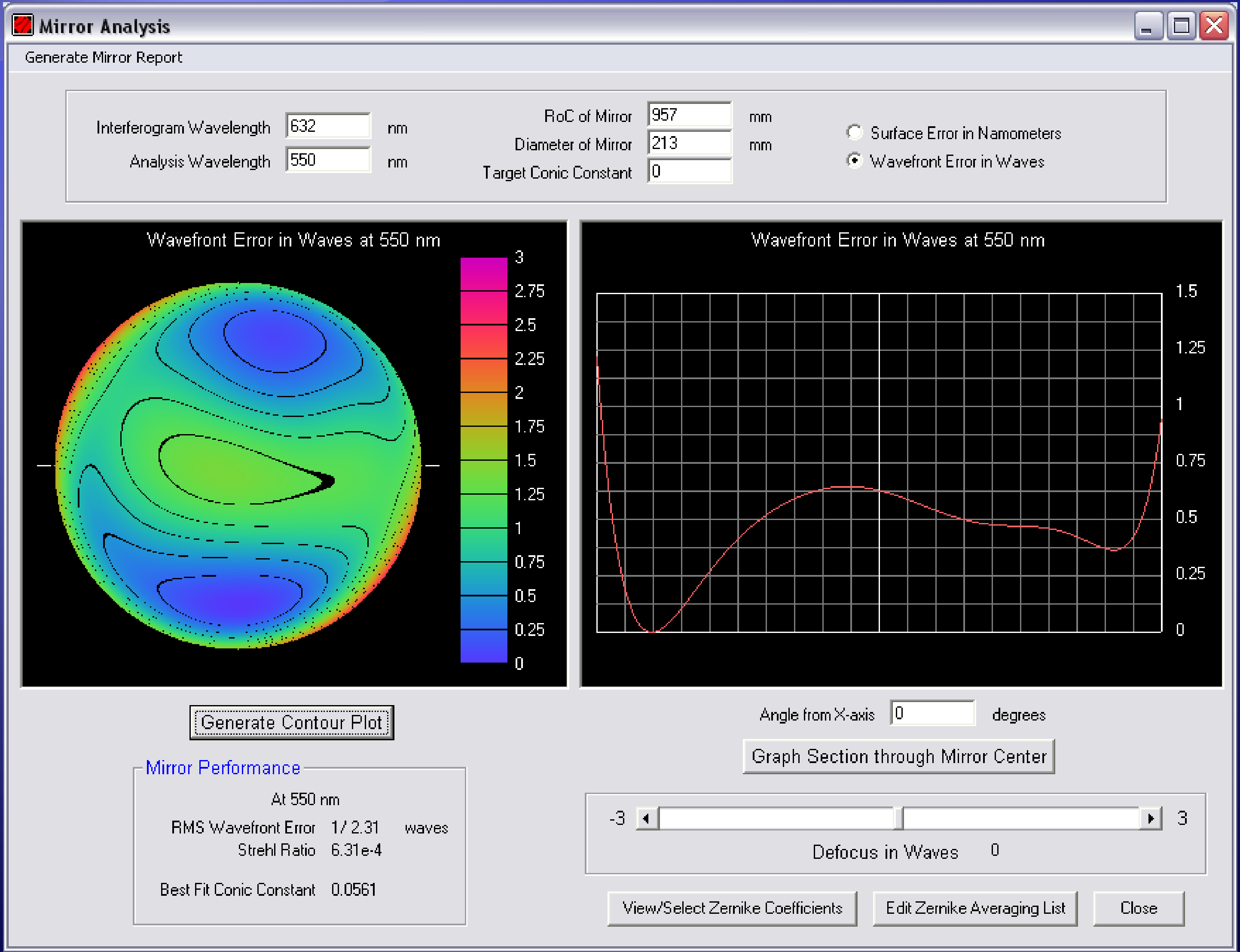


Starstone evaluation I



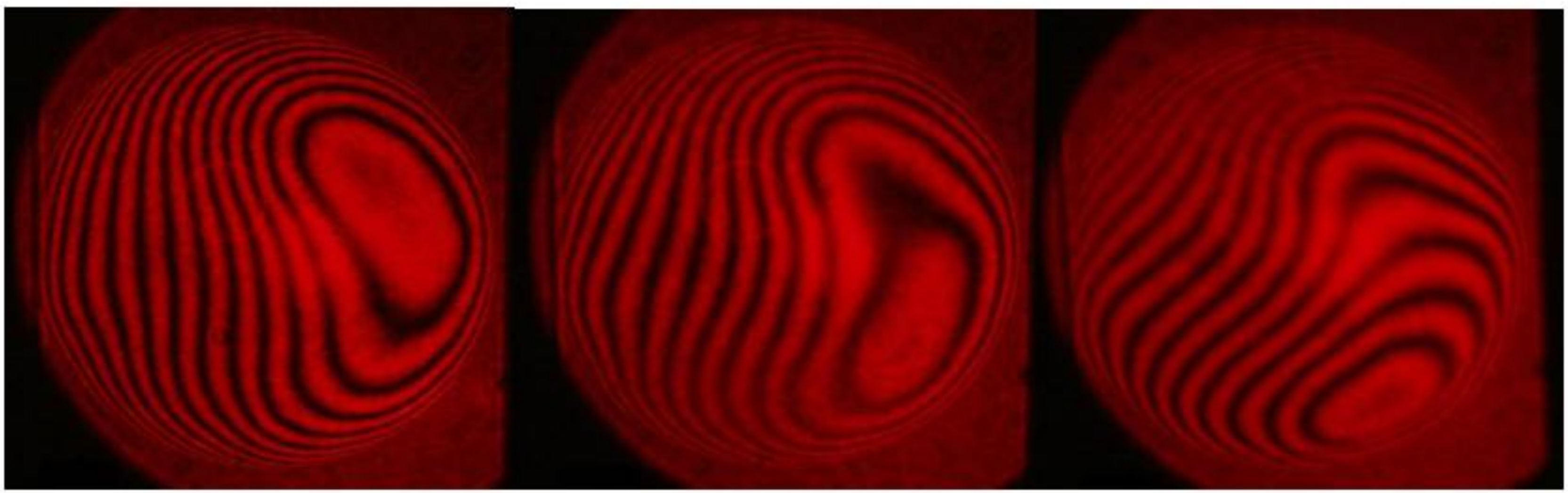
- Mirror 0001A 8″ f/2.25

Starstone evaluation II



Starstone evaluation III

- Cooling after 30 sec. warming with heat gun

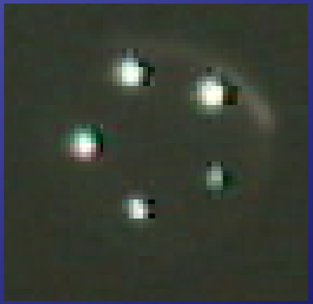


7:32:26pm 7:32:54pm 7:33:52pm

Starstone evaluation IV

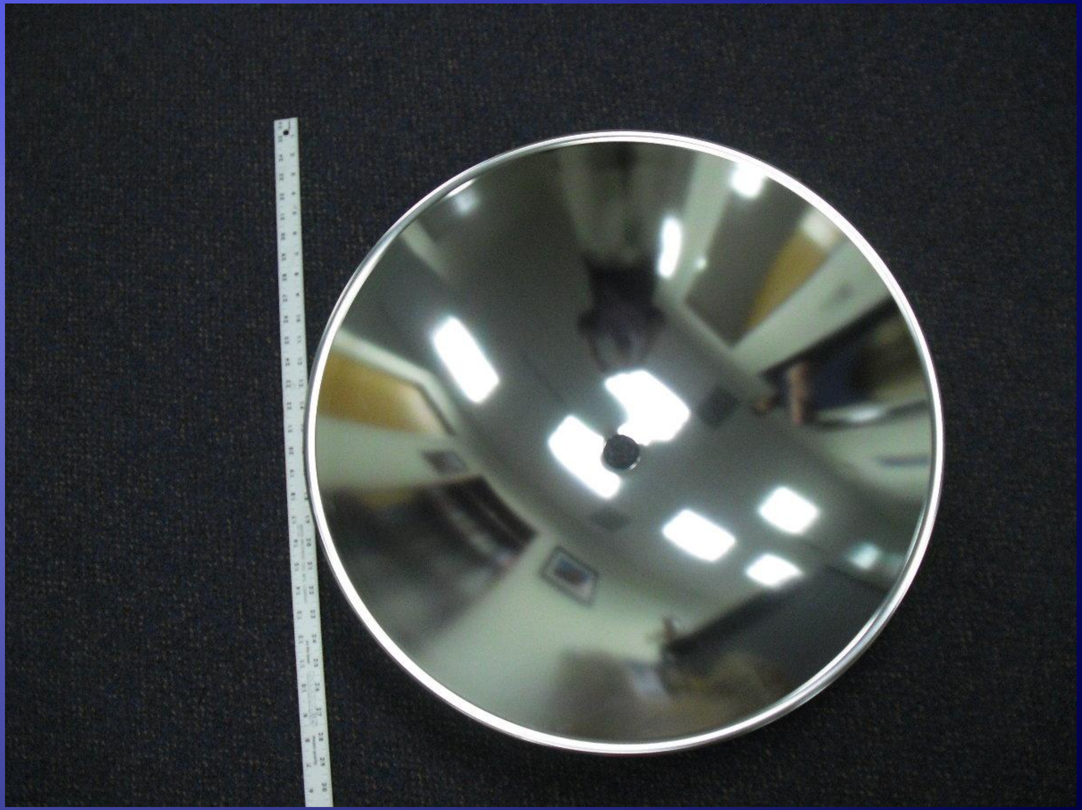
- Corrector used– 50-mm projection lens
- Hubble optics 5-star flashlight 50 to 250 micron "stars" @11-m
- 180″ – no correction

- 25″ – with correction

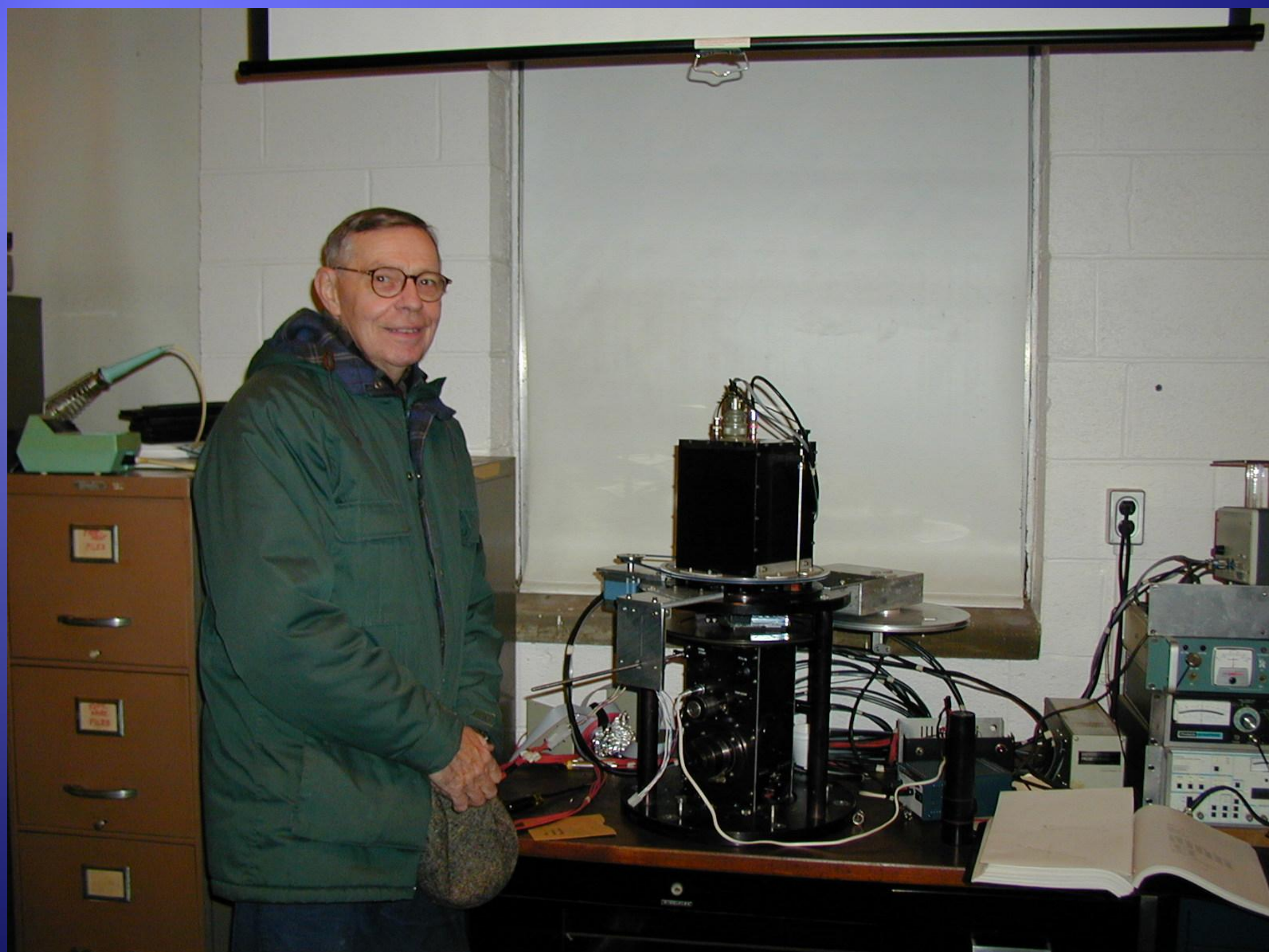


Other Potential LBT Mirrors

- Edmund 24" parabolic
- Aluminum 0.04"
- f/0.25
- 1.5" central hole
- Low reflectivity (not "precision polished")
- We are eager to evaluate other mirrors



In Memoriam
Robert H. Koch 1929-2010



Contact

- Email: bholenstein@gravic.com
- Initiative Website - www.AltAzInitiative.org
- Yahoo Discussion Group - http://groups.yahoo.com/group/AltAzInitiative

More details:
The Alt-Az Initiative: Telescope, Mirror, & Instrument Developments, eds. Genet, Johnson, & Wallen, (Payson, AZ: Collins Foundation Press) 2010