GMT
Primary Mirror Optical Test Alignment Sensitivities

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OPTI696B Practical Optics

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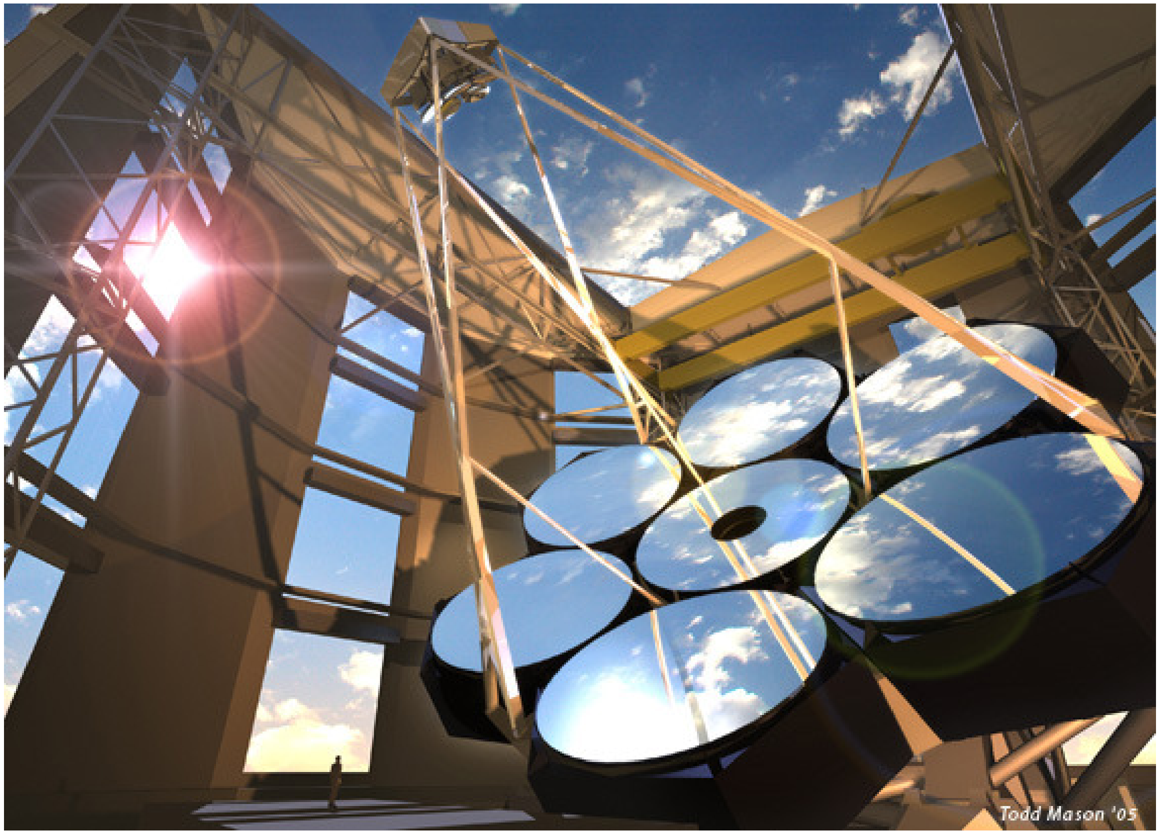
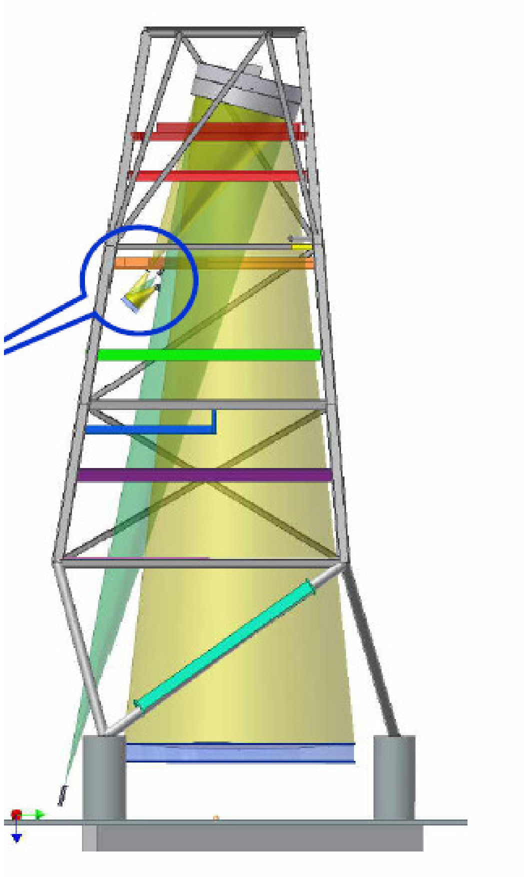
The Giant Magellan Telescope (GMT)

- This mirror is composed of seven 8.4m segments, six of which will be off-axis segments
- The primary mirror is a hyperbola – a parabola with spherical aberration



A description of the problem

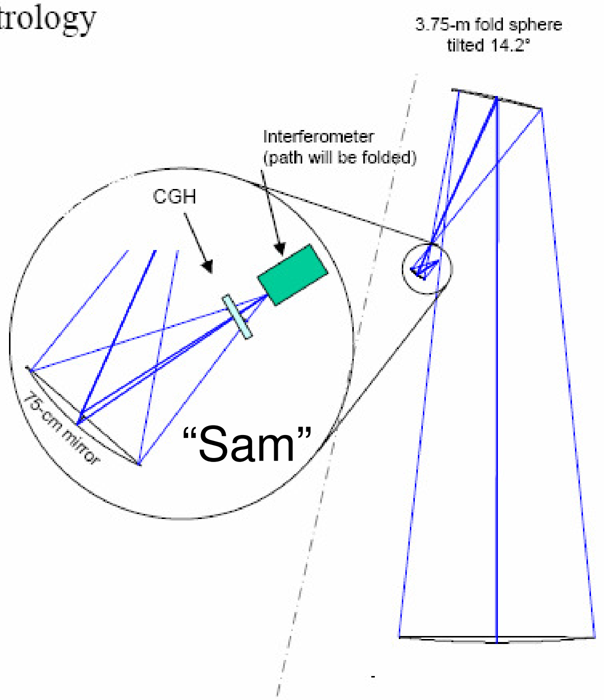
- The GMT off-axis parabolic mirror segments will be tested using a Computer Generated Hologram
- Alignment errors of the CGH and the fold mirrors will lead to measurement errors in the surface of primary mirror



Measurements

Alignment of principal test

- Alignment of 75-cm mirror with CGH and interferometer
  - ~10 µm tolerances
  - As a system this is aligned and fixed in the tower.
  - Use NST heritage + CMM + C of C reference for metrology
- Alignment of 3.75-m fold sphere
  - ~100 µm tolerances
  - Use *in situ* laser tracker for metrology
  - Move the big FS according to tracker
- Alignment of GMT to optical test
  - ~200 µm tolerances
  - Use *in situ* laser tracker
  - Add optical projections
  - Move GMT segment for alignment



Error analysis for principal test

- Given alignment tolerances, the goals are to find:
  - Force required to bend primary mirror to correct errors in the mirror due to testing
  - Structure function for errors that were not corrected by bending

- This is a problem that I worked on last spring for my research, and I am currently revisiting…

Procedure for error analysis

For each degree of freedom:

1. Simulate perturbation of test optics
2. Simulate optimization in telescope using mirror radial position and clocking

Chunyu

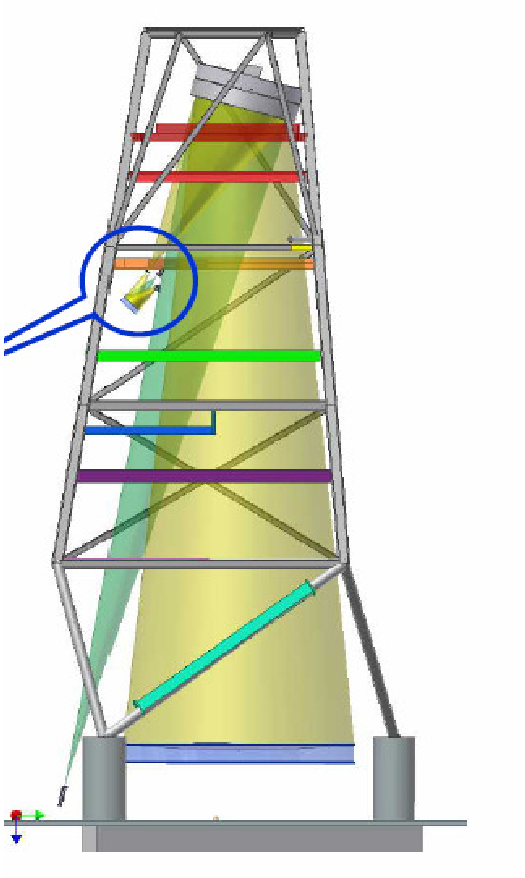
3. Simulate bending
4. Evaluate residual wavefront

My work

Combine effects of all degrees of freedom using RSS

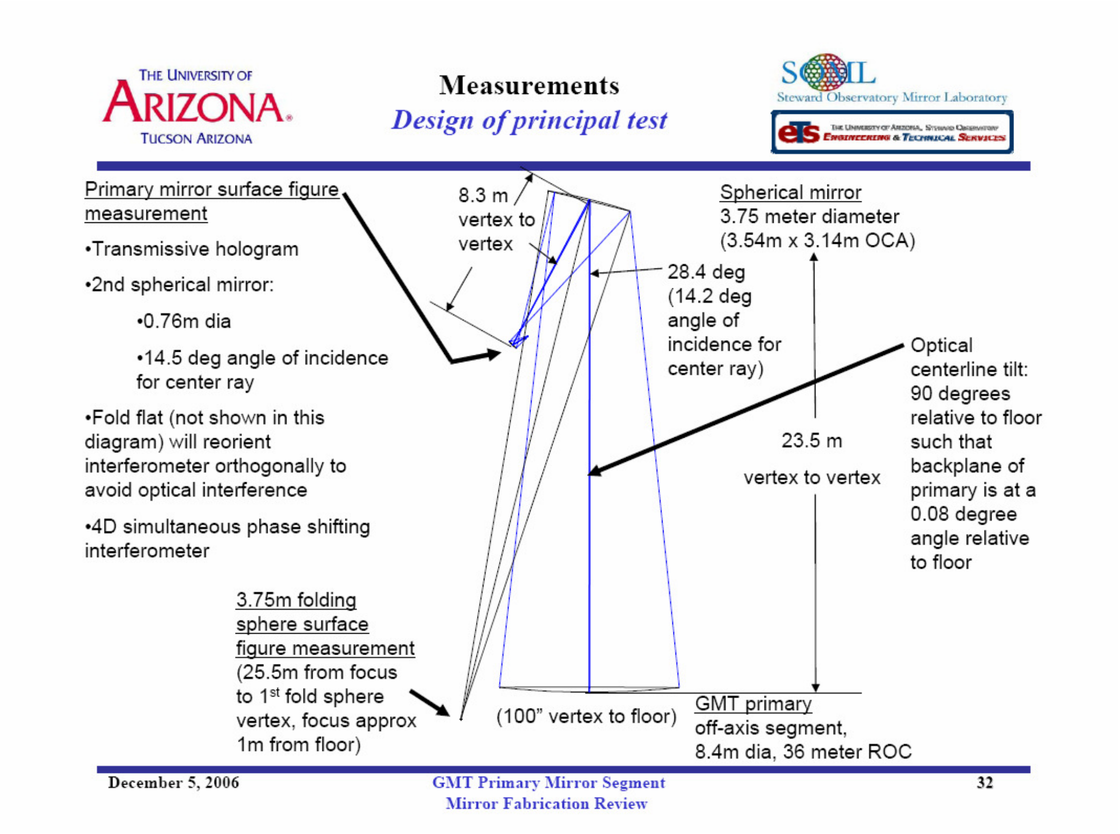
Degrees of Freedom

Element	Parameter	Tolerance (μm)
hologram	axial displacement	20
	tilt about *y*	10
	tilt about *x*	10
3.75 m sphere	axial displacement	100
	tilt about *y*	100
	tilt about *x*	100
	radius	250
0.75 m sphere	axial displacement	20
	tilt about *y*	10
	tilt about *x*	10
	radius	20
GMT segment	axial displacement	200



Step 1: Simulate perturbation of test optics

- Model the optical system in Zemax
- Perturb each degree of freedom individually and record the resulting wavefront in terms of Zernike coefficients



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Measurements

Design of principal test

SOML Steward Observatory Mirror Laboratory
eTS The University of Arizona, Steward Observatory Engineering & Technical Services

Primary mirror surface figure measurement

- Transmissive hologram
- 2nd spherical mirror:
  - 0.76m dia
  - 14.5 deg angle of incidence for center ray
- Fold flat (not shown in this diagram) will reorient interferometer orthogonally to avoid optical interference
- 4D simultaneous phase shifting interferometer

8.3 m vertex to vertex

Spherical mirror
3.75 meter diameter
(3.54m x 3.14m OCA)

28.4 deg (14.2 deg angle of incidence for center ray)

Optical centerline tilt: 90 degrees relative to floor such that backplane of primary is at a 0.08 degree angle relative to floor

23.5 m vertex to vertex

3.75m folding sphere surface figure measurement (25.5m from focus to 1st fold sphere vertex, focus approx 1m from floor)

(100" vertex to floor)

GMT primary off-axis segment, 8.4m dia, 36 meter ROC

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GMT Primary Mirror Segment Mirror Fabrication Review

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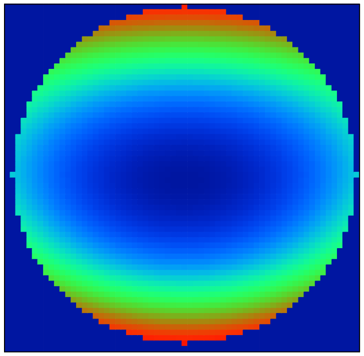
Step 2: Simulate optimization in telescope

- In Excel: optimize the position of the mirror segment in the telescope and find the new Zernike coefficients for the resulting wavefront
  - We have two easy degrees of freedom for correcting low order errors by moving the mirror segment in the telescope
  - Adjustment for each degree of freedom has the same OPTICAL effect as changing the mirror shape by the appropriate amount

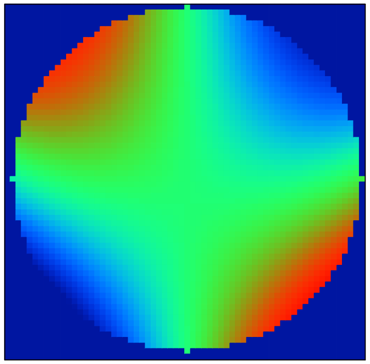
<u>1 mm radial motion</u>



4.2 µm pv
0.97 µm rms

0.81 µm rms power
0.55 µm rms astigmatism
0.05 µm rms coma
0.02 µm rms trefoil

<u>50 arcsec clocking</u>
(1 mm motion at outer edge of mirror segment)



6.59 µm pv
1.29 µm rms

1.28 µm rms astigmatism
0.17 µm rms coma
0.02 µm rms trefoil

Step 3: Simulate bending (my work)

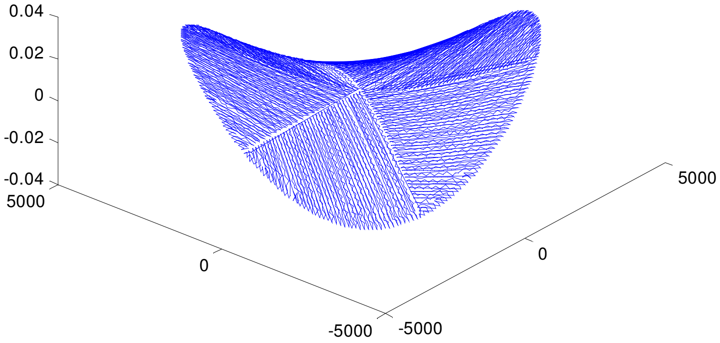
- What I was given:
  - Zernike coefficients for the wavefront for each degree of freedom (up to Zernike 37)
  - 165 GMT primary mirror segment bending modes

- Goal: figure out which bending modes and how much of them are needed to bend out the resulting wavefront and find out what is left over

Step 3: Simulate bending, continued

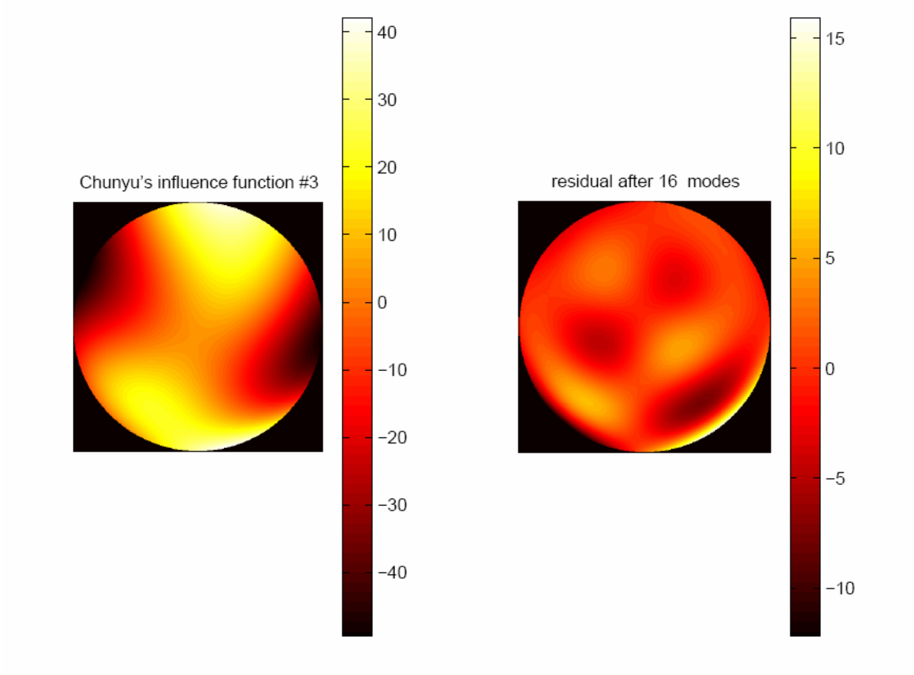
- Steps done in Matlab
  - Load bending modes of the mirror (calculated by SVD analysis)
    - Each one is described by 6991 x, y, z points
  - Calculate each (of the first 37) Zernike coefficient in terms of those same x and y coordinates.
  - Do a least squares fit to decompose each bending mode into Zernike coefficients
    - This can be done easily with back slash operator in Matlab
      - `ZernCoef = zernpolys \ U(:,modenum);`

The lowest order bending mode of the mirror looks very much like astigmatism



Step 3: Simulate bending, continued

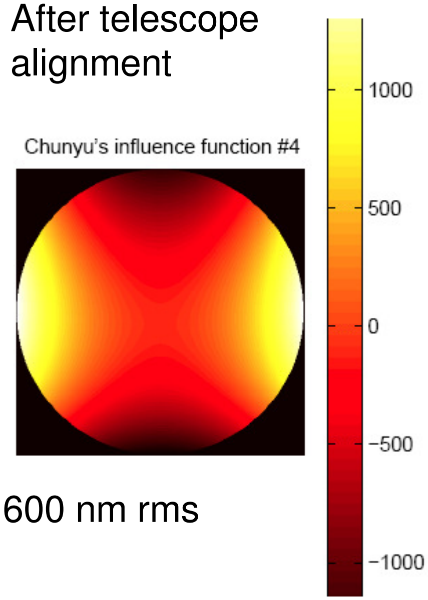
- Load the Zernike coefficients describing each DOF (“influence functions”)
- Do a least squares fit to determine the best amount of each bending mode needed to correct the influence function
  - We used 16 modes to make corrections
  - More modes require more force, but provide better correction



Step 3: Simulate bending, continued

- The residual, after fit is determined and represented using Zernikes
- For our example of 100 µm fold sphere position error

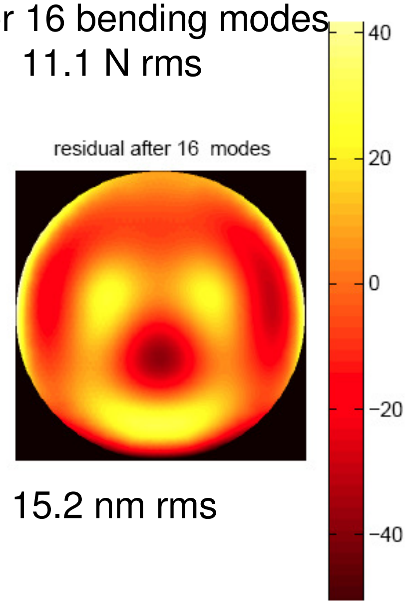
After telescope alignment



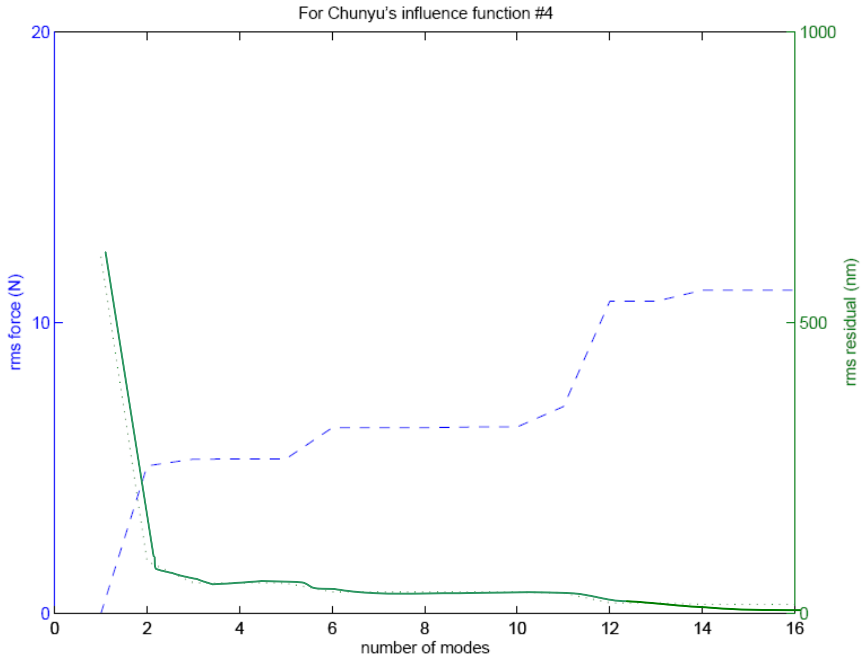
600 nm rms

After 16 bending modes

F = 11.1 N rms



15.2 nm rms

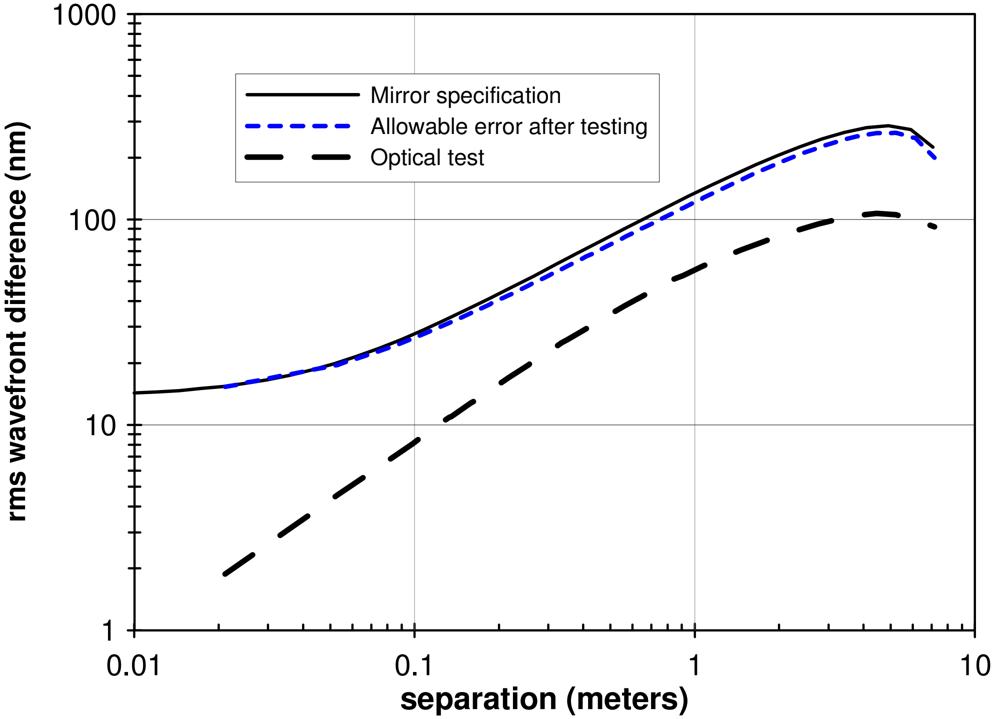


Step 4: Evaluate residual wavefront

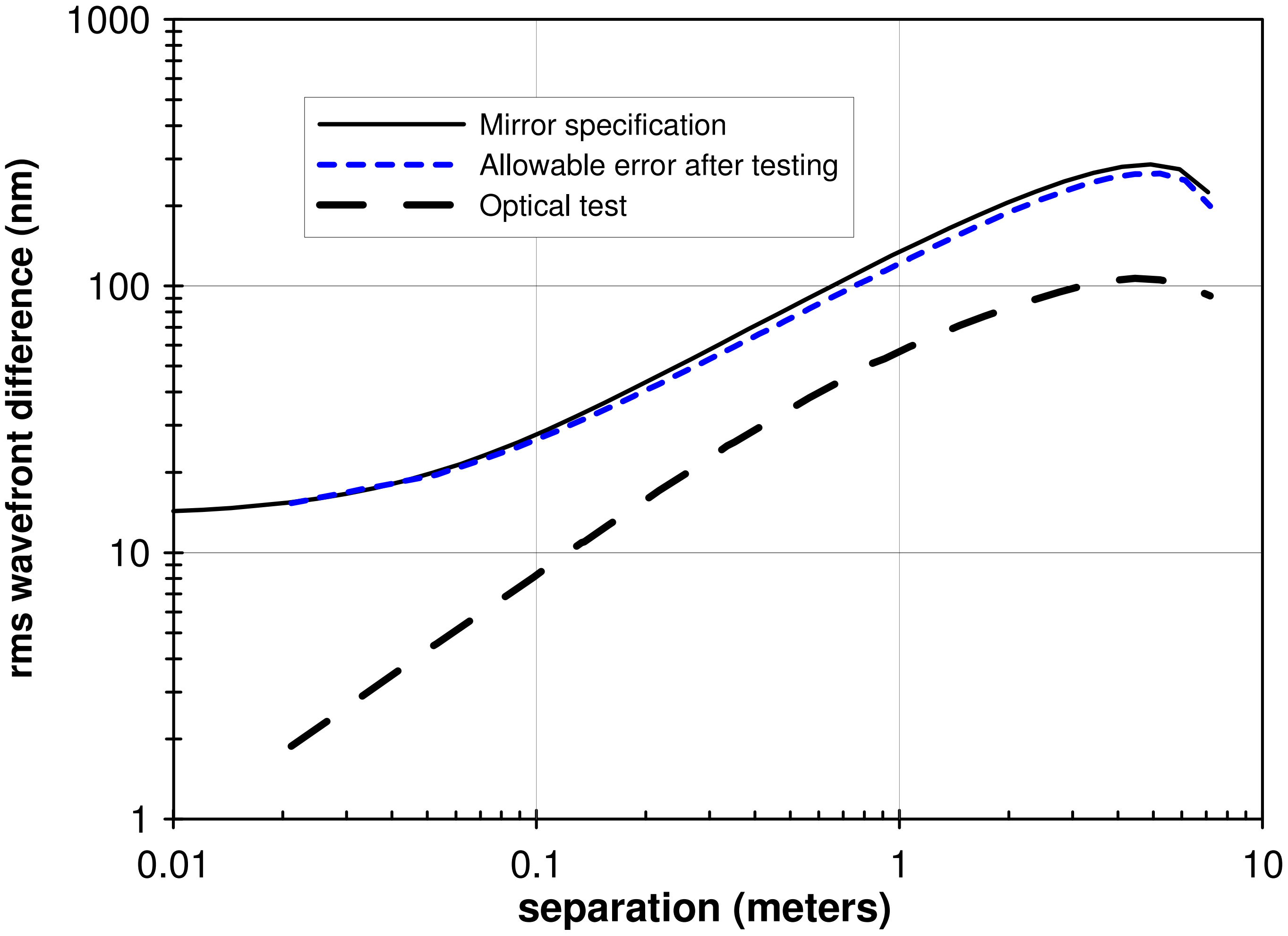
- For each Zernike term, structure functions, defined as mean square phase difference between points on the mirror with separation d, were calculated. Call these $S_i(d)$ (units are nm^2)
- The residual after bending is represented using Zernikes coefficients a_i
- The structure function representing the residual is then computed as

$$S(d) = \sum a_i S_i(d)$$

(Note, we show the ***square root*** of the structure function so the units make more sense)



Structure function for GMT optical test



Results

TABLE 1. RESULT OF TOLERANCE ANALYSIS FOR THE OPTICAL ALIGNMENT OF THE GMT NULL TEST

Element	Parameter	Tolerance (µm)	Radial shift (mm)	Clocking (mdeg)	Correction force (N rms)	Residual surface (nm rms)
hologram	axial displacement	20	0.02	0.25	5.44	11.95
	tilt about *y*	10	-0.01	0.16	0.99	2.80
	tilt about *x*	10	-0.02	0.02	3.16	8.27
3.75 m sphere	axial displacement	100	1.23	-0.05	11.12	15.21
	tilt about *y*	100	0.00	3.11	1.88	4.19
	tilt about *x*	100	1.04	-0.04	8.05	20.09
	radius	250	-0.40	0.01	2.84	3.10
0.75 m sphere	axial displacement	20	-0.50	0.02	5.02	6.16
	tilt about *y*	10	0.00	-0.10	2.11	3.14
	tilt about *x*	10	0.12	-0.01	3.94	9.80
	radius	20	-0.49	0.02	4.98	6.89
GMT segment	axial displacement	200	0.40	-0.02	4.67	8.56
sum in quadrature			1.85	3.13	18.23	33.85

Lessons Learned from this project

- On work in general:
  - Document your work immediately when you finish something, so you don’t have to figure it out again later
    - Jim would say document as you go…
  - While it is often good to archive old files, if you keep too much stuff (that is obviously wrong), you might get confused looking through it later
- On Matlab
  - You can never have too many comments in your code
  - Separate different functions into different files

References

- GMT Primary Mirror Segment Mirror Fabrication Review
  - GMT2006DEC5MirrorFabReviewReviewVersion1.1Final.pdf
- Jim Burge's presentation: testing analysis.ppt