

# Metrology of LIGO Optics using Fizeau Interferometry

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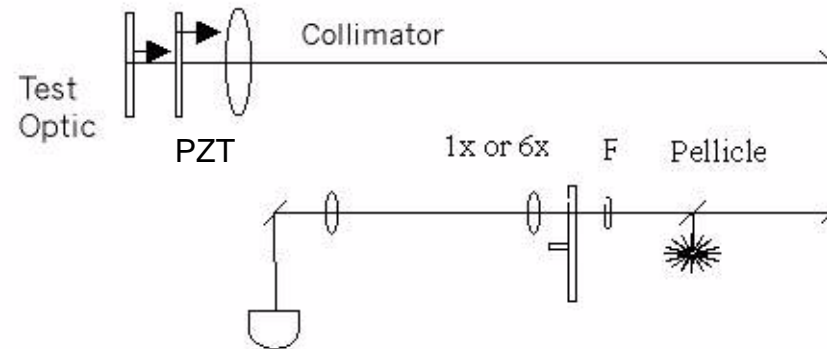
# LIGO Core Optic Specifications

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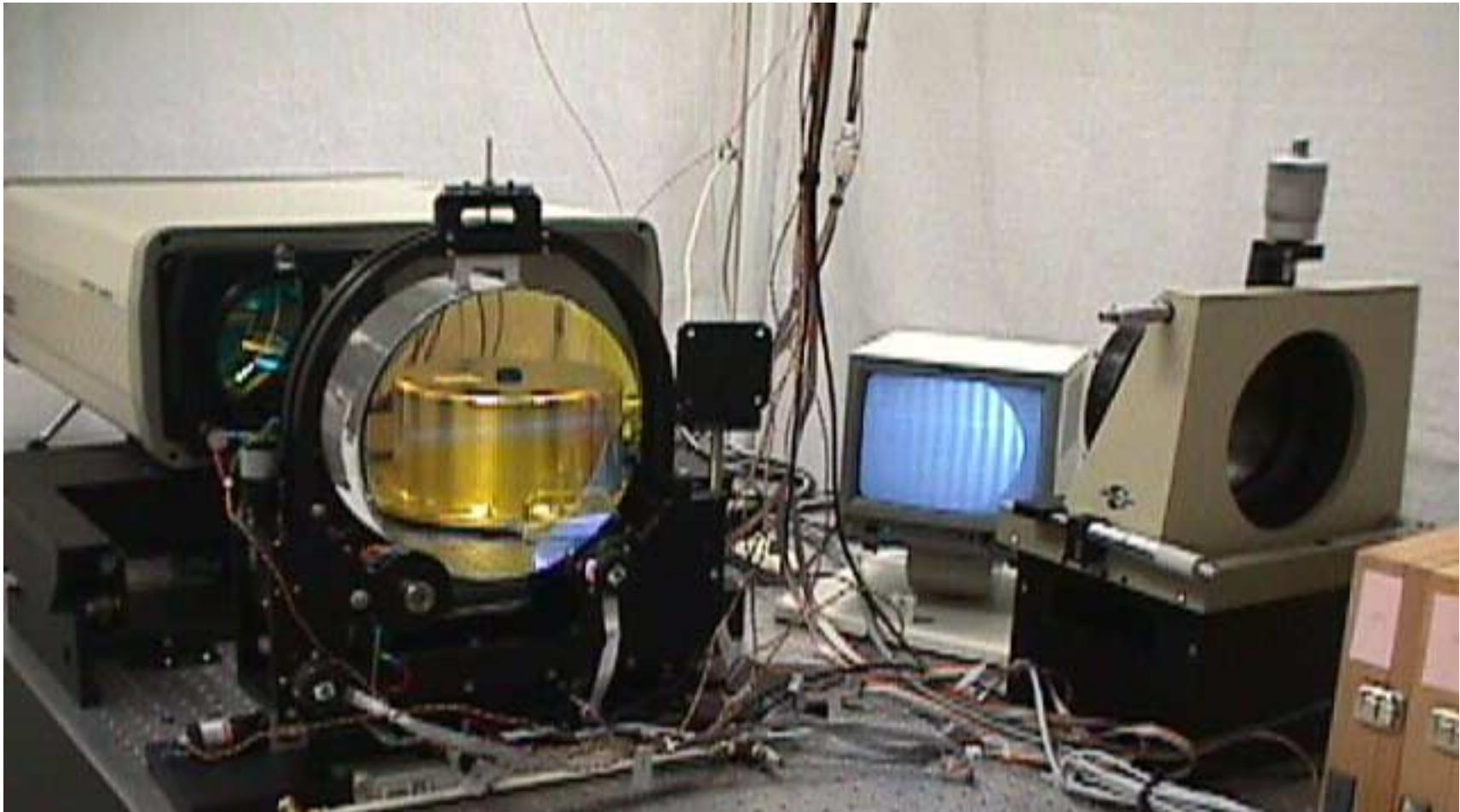
## Test Masses have the most stringent requirements

- ››  $\sigma_{\text{rms}} < 0.8$  nm over the central 80 mm diameter (~beam waist for LIGO1)
  - With Tilt, Power and Astigmatism subtracted
  
- ›› Radius of curvature must match to <1.5% and be accurate to <3%
  - Corresponds to a repeatability of < 5nm and an accuracy of < 10 nm

# The interferometer



- 150 mm aperture
- Measurements made at 1064 nm (usu 632 nm)
- Longer movement in PZTs, 2 waves of travel (usu 1 wave)
- Fixed Zoom: 25mm and 150mm (usu variable zoom)
- 6 Custom Reference Flats
- Able to measure High Reflectors using special “Clapham-Dew” coating on 2 of the Reference Flats.





## Data

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Dataset = average of 8 measurements (takes about 1 minute)

for each optic we measure:

Arrow at  $0^\circ$

Arrow at  $45^\circ$

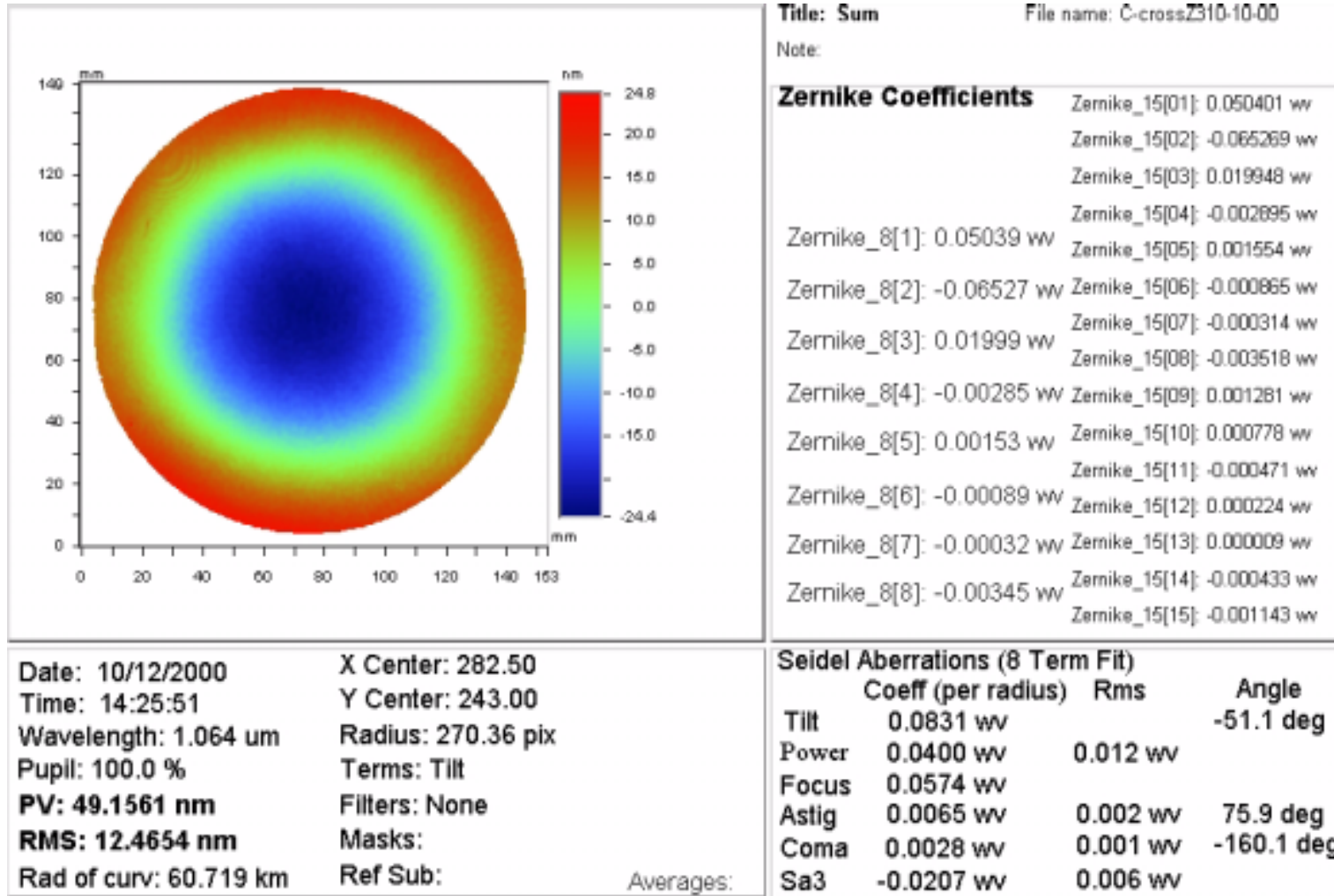
Arrow at  $90^\circ$

Arrow at  $180^\circ$

Arrow at  $0^\circ$ , off axis by 35mm

Arrow at  $0^\circ$ , zoom to 6x

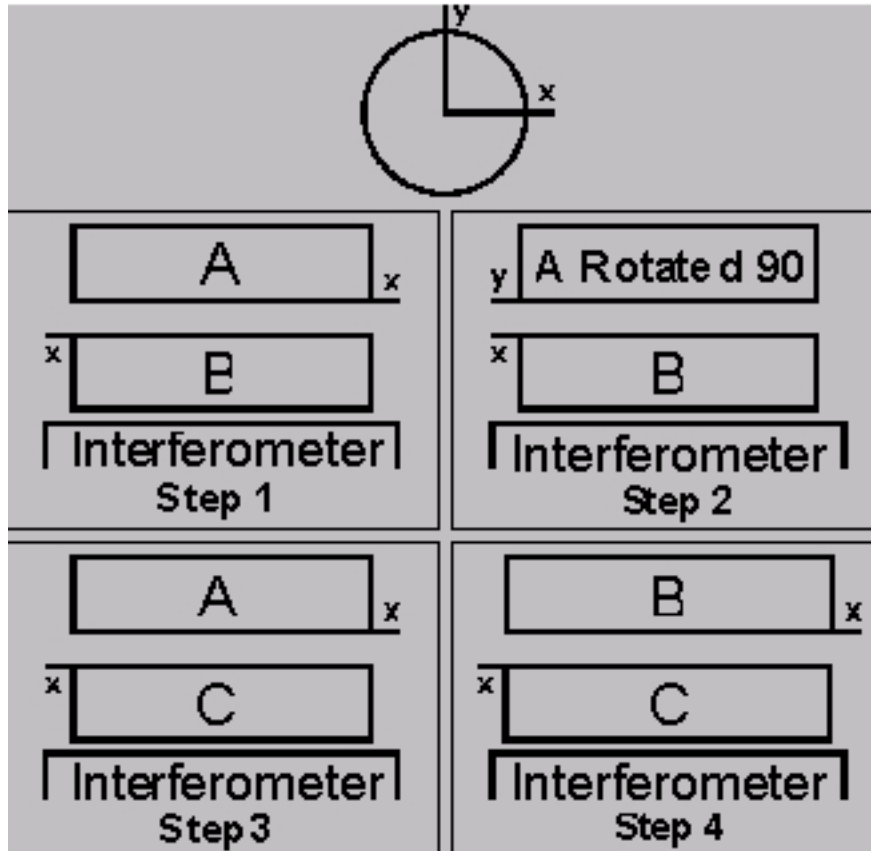
# “C” Flat Reference Data Set



# Zernike Polynomials

Wyko	$R_n^m(\rho) \begin{cases} \cos m\theta \\ \sin m\theta \end{cases}$	Description	Born & Wolf	
			Radial n	Azimuthal m
0	1	Piston	0	0
1	$\rho \cos \theta$	X-Tilt	1	1
2	$\rho \sin \theta$	Y-Tilt		
3	$2\rho^2 - 1$	Power	2	0
4	$\rho^2 \cos 2\theta$	Astigmatism, axis at $0^\circ$	2	2
5	$\rho^2 \sin 2\theta$	Astigmatism, axis at $45^\circ$		
6	$(\rho^3 - 2\rho) \cos \theta$	3rd order Coma, y-axis	3	1
7	$(\rho^3 - 2\rho) \sin \theta$	3rd order Coma, x-axis		
8	$6\rho^4 - 6\rho^2 + 1$	3rd order Spherical Aberration	4	0
9	$\rho^3 \cos 3\theta$	Tri-Foil, base of y-axis	3	3
10	$\rho^3 \sin 3\theta$	Tri-Foil, base of x-axis		

# Calibration: Three Flat Test



››4 cavity measurements

››“Absolute” results along the zero and ninety degree diameters.

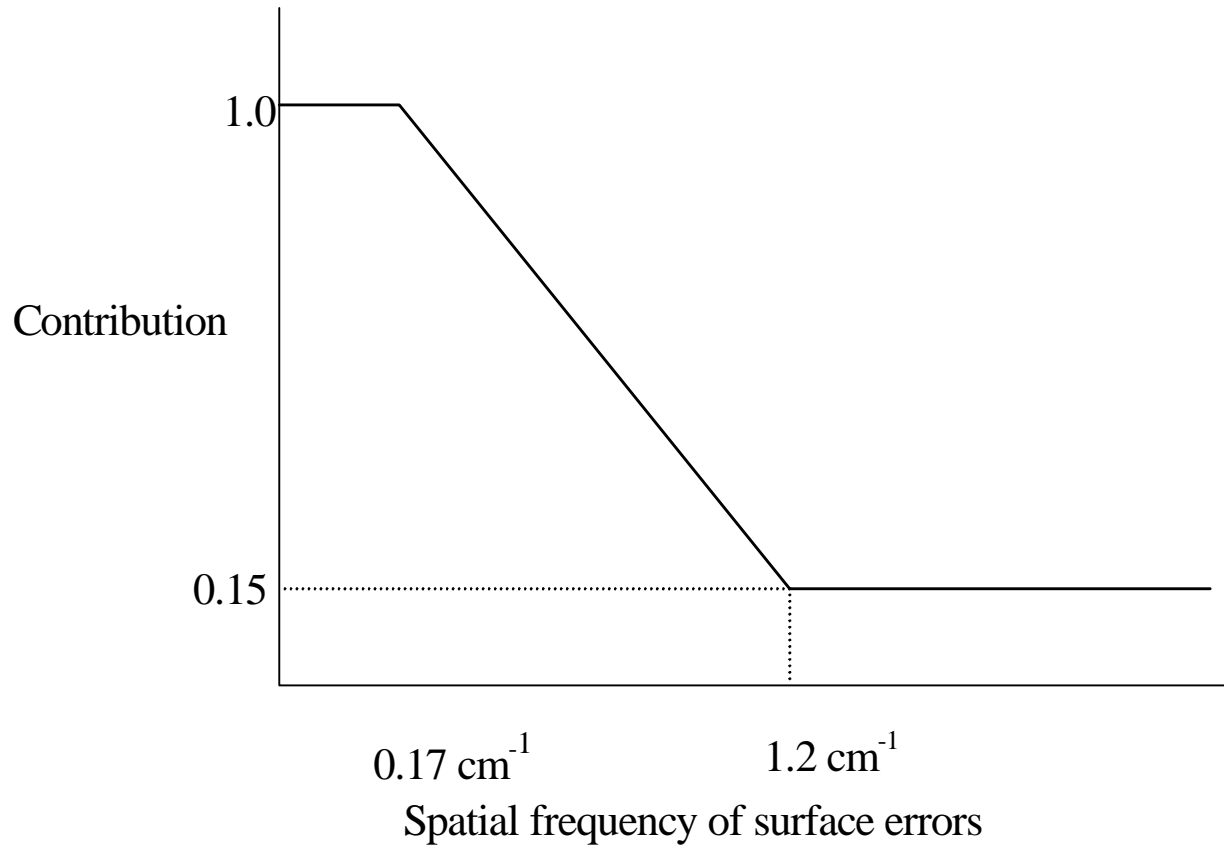
››Approximate results elsewhere.

— Chiayu Ai and James C. Wyant, “Absolute testing of flats by using even and odd functions,” *Appl. Opt.* **32**, 4698-4705 (1993).





# LIGO High Spatial Frequency Calibration



(P. Hariharan “Optical flat surfaces: direct interferometric measurement of small scale surface irregularities”, Opt. Eng. 35 3265-3266 (1996).)



## Reference Map

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Reference Map =  $Z_3$  (TFT) + AVG(all "C" measurements -  $Z_3$ )

Optic = Cavity measurement - Reference Map



# Noise Sources

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Thermal Noise (turbulence and alignment drift)

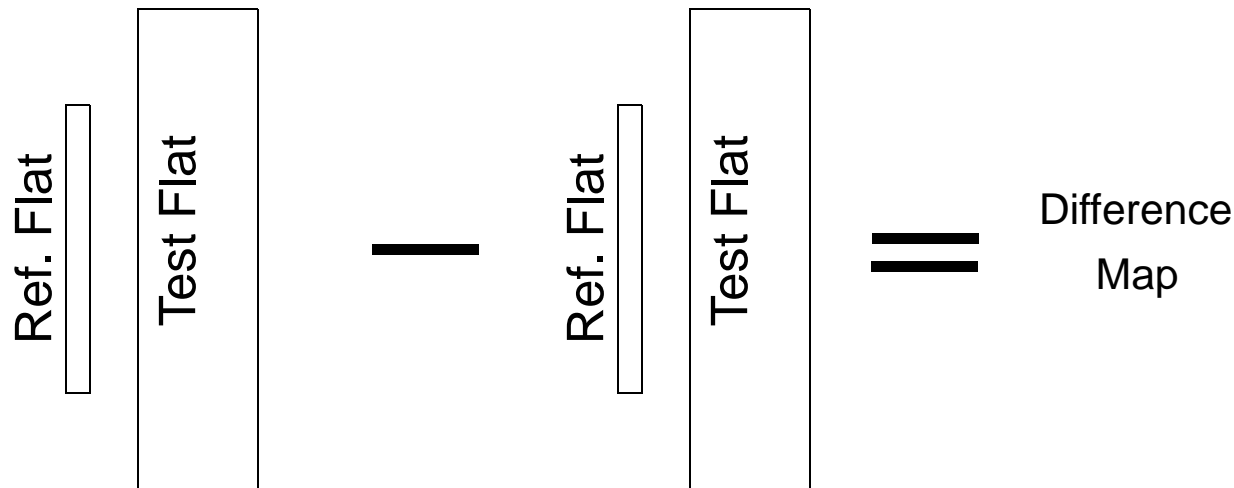
Camera Noise

Vibration



# Difference Maps Uncover Noise

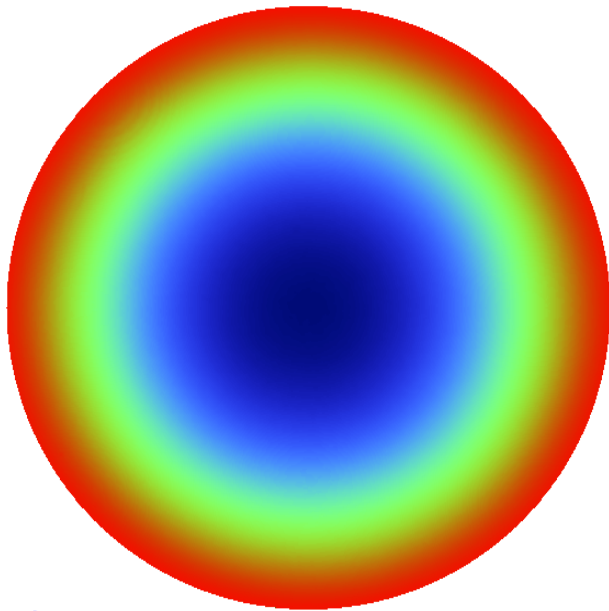
Subtract two cavity measurements in software



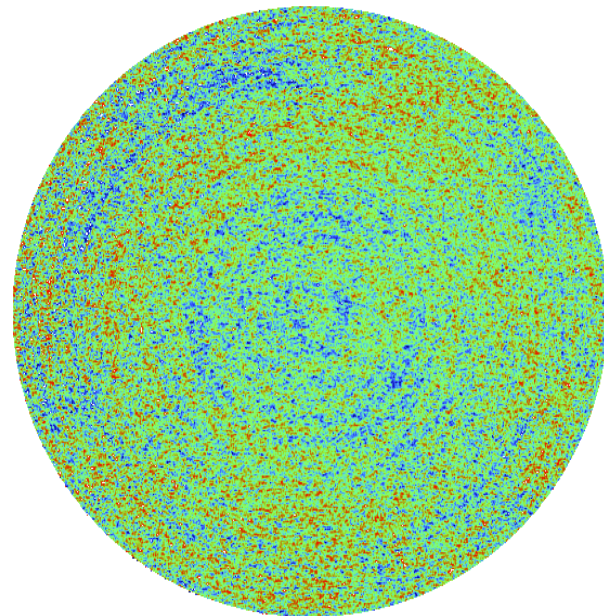


# Cavity difference (short term) ~ 0.14 nm rms

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Cavity Measurement

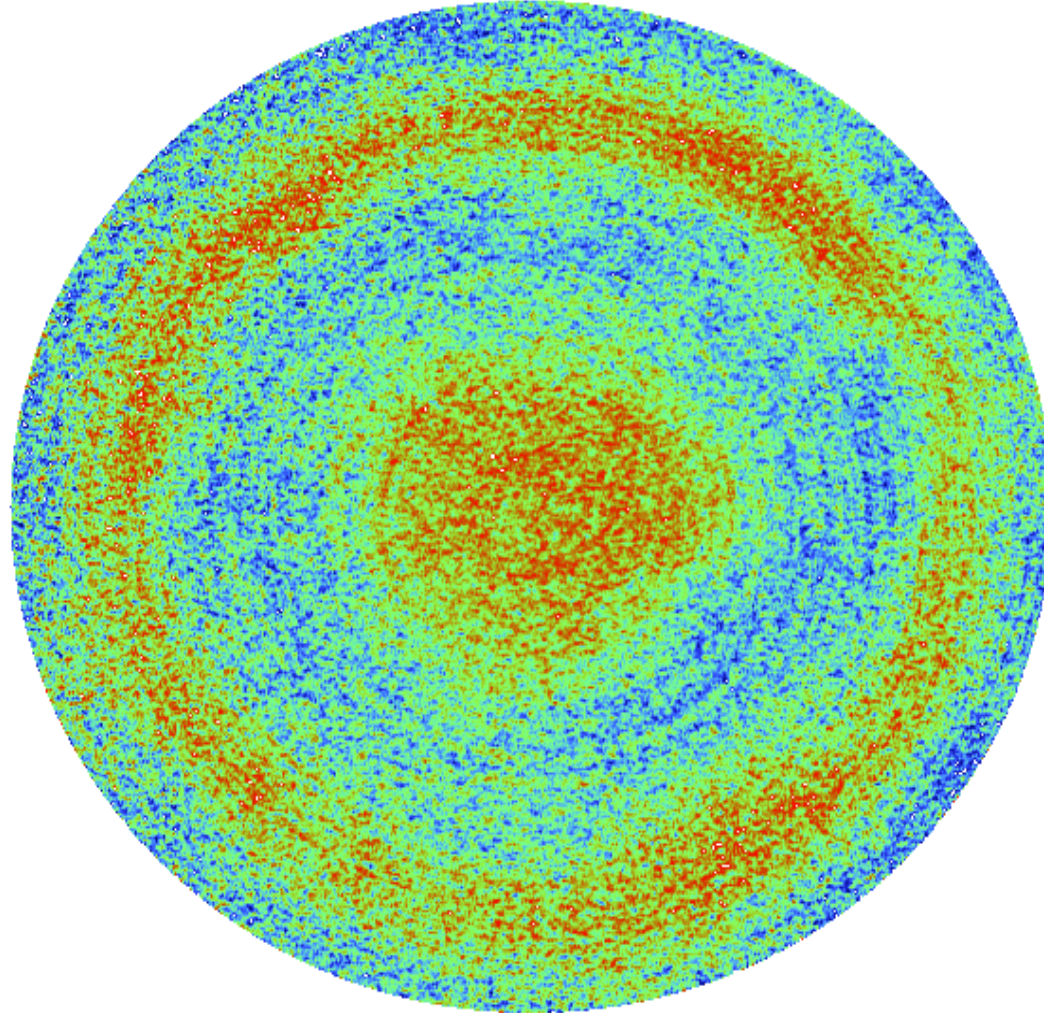


Difference in consecutive  
Cavity Measurements



# Cavity Difference (short term) Evidence of Vibration $\sim 0.15$ nm rms

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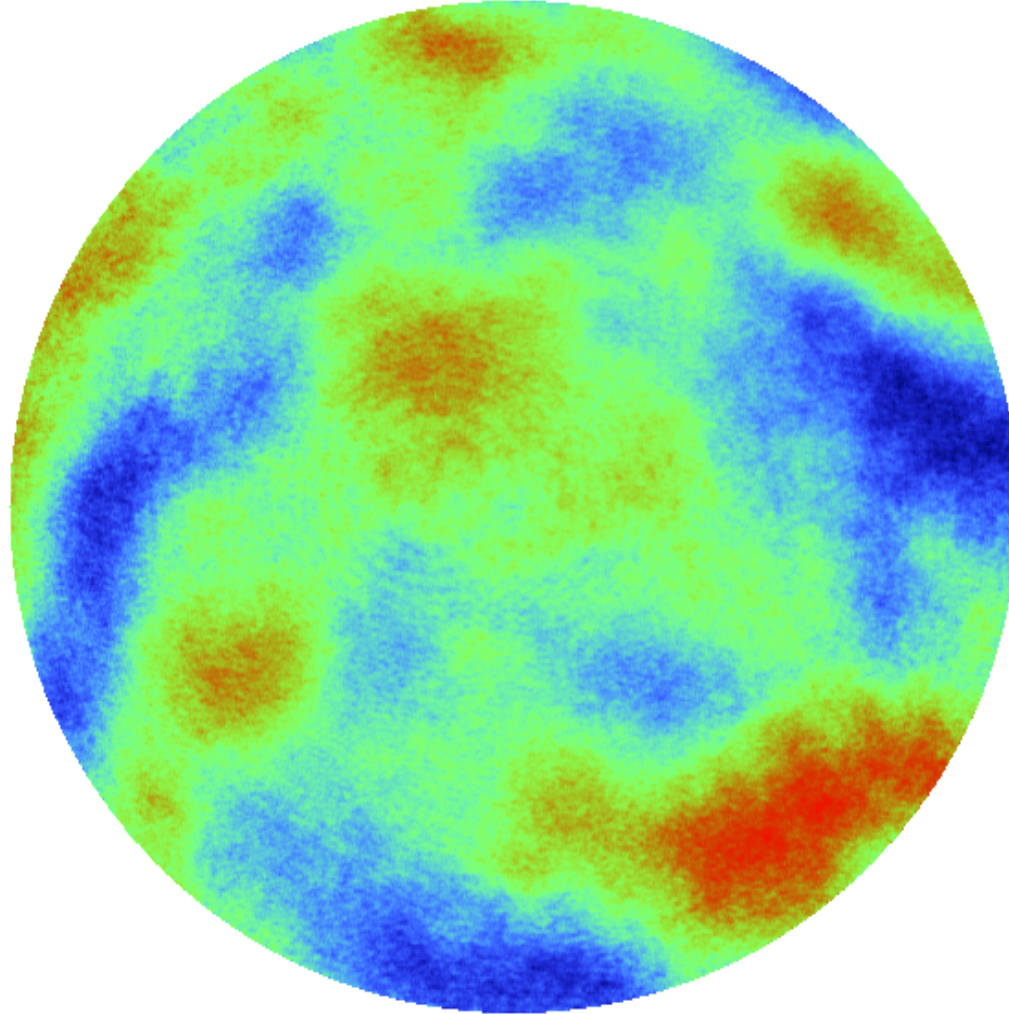




**LIGO**

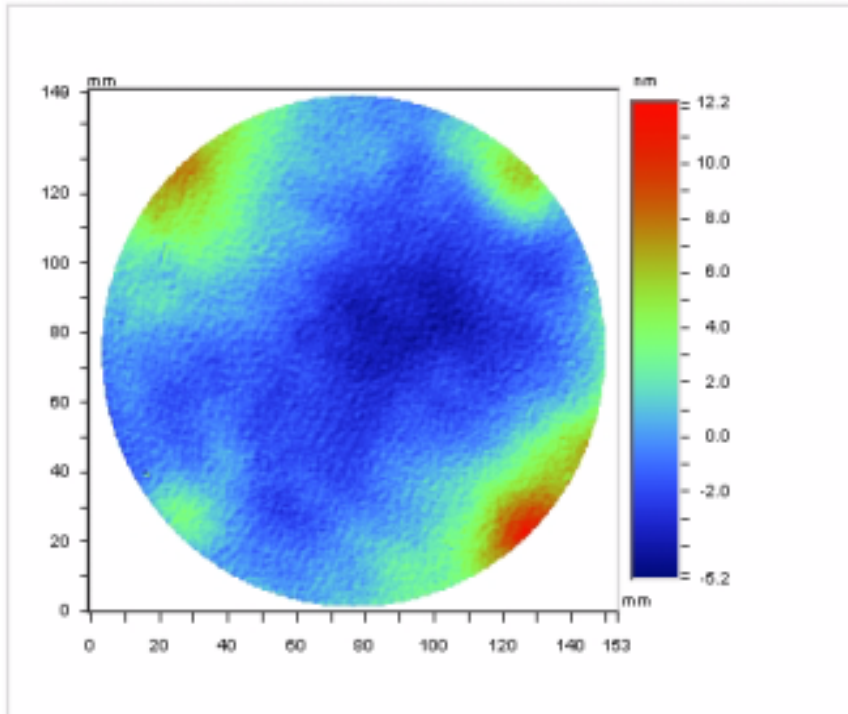
# Cavity Difference (long term) Evidence of Turbulence $\sim 1.0$ nm rms

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# Change in Reference flat over 5C°



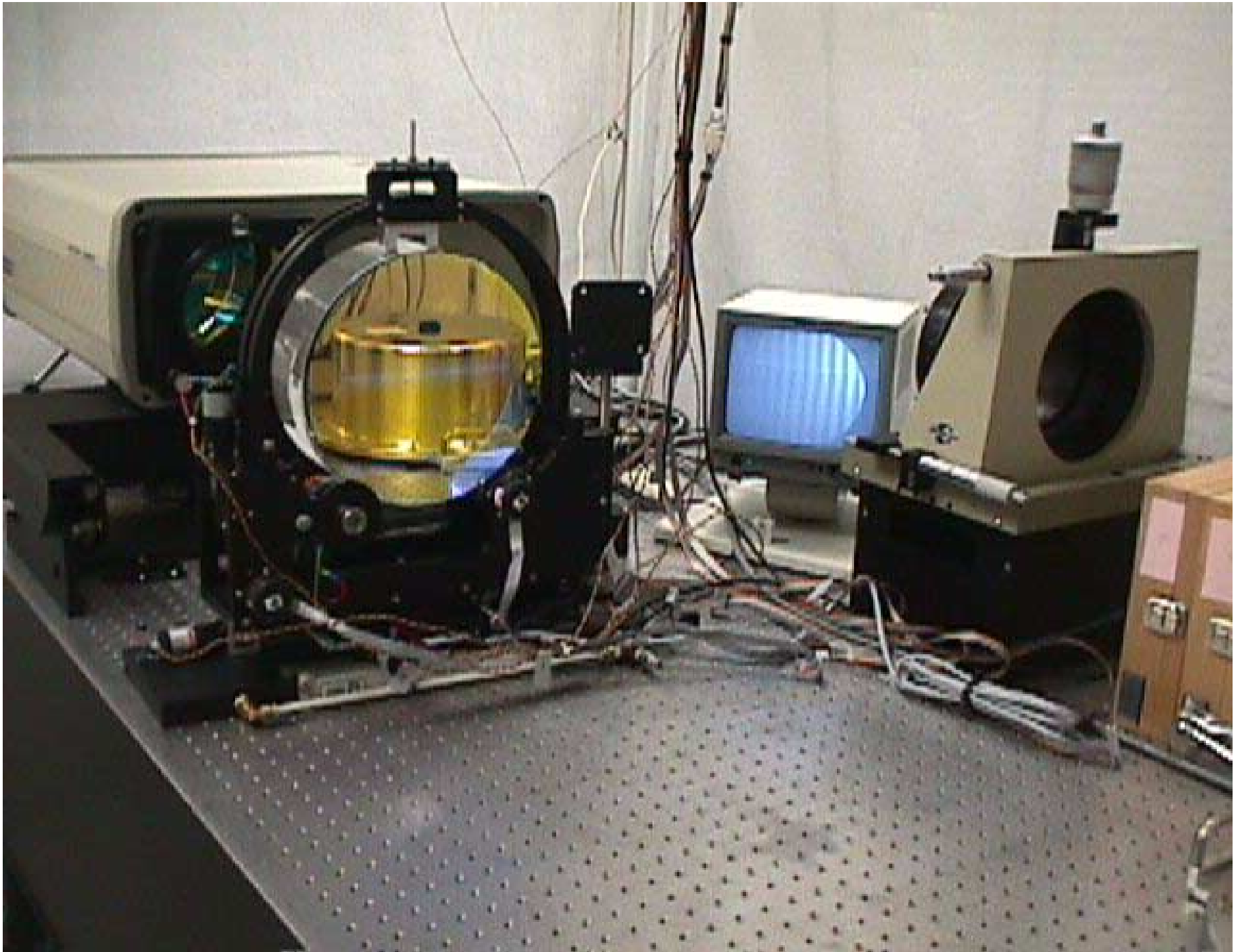
Title: Delta\_5C-Flat File name: Delta\_5C-C flat  
 Note: 20C\_C\_FM)2-0\_044-C\_FM02-0\_094

Zernike Coefficients	
Zernike_8[1]: 0.01631 wv	Zernike_15[01]: 0.016304 wv
Zernike_8[2]: -0.000771 wv	Zernike_15[02]: -0.008707 wv
Zernike_8[3]: 0.00278 wv	Zernike_15[03]: 0.002787 wv
Zernike_8[4]: -0.00030 wv	Zernike_15[04]: -0.000292 wv
Zernike_8[5]: -0.00272 wv	Zernike_15[05]: -0.002731 wv
Zernike_8[6]: 0.00142 wv	Zernike_15[06]: 0.001404 wv
Zernike_8[7]: -0.00004 wv	Zernike_15[07]: -0.000032 wv
Zernike_8[8]: -0.00007 wv	Zernike_15[08]: -0.000063 wv
	Zernike_15[09]: -0.000358 wv
	Zernike_15[10]: -0.000058 wv
	Zernike_15[11]: 0.000386 wv
	Zernike_15[12]: 0.000476 wv
	Zernike_15[13]: -0.000063 wv
	Zernike_15[14]: -0.000104 wv
	Zernike_15[15]: 0.000058 wv

Date: 03/19/1999 X Center: 288.00  
 Time: 14:52:45 Y Center: 239.00  
 Wavelength: 1.064 um Radius: 275.48 pix  
 Pupil: 100.0 % Terms: Tilt  
**PV: 17.4223 nm** Filters: None  
**RMS: 2.4417 nm** Masks:  
 Rad of curv: 455.653 km Ref Sub:  
 Averages:

Seidel Aberrations (8 Term Fit)			
	Coeff (per radius)	Rms	Angle
Tilt	0.0160 wv		-32.6 deg
Power	0.0056 wv	0.002 wv	
Focus	0.0032 wv		
Astig	0.0055 wv	0.001 wv	-48.1 deg
Coma	0.0043 wv	0.002 wv	-1.5 deg
Sa3	-0.0004 wv	0.000 wv	







## Changes in the Lab

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Added an insulated aluminum box which surrounds the optic and reference flat

Added a thermostat controlled valve on the chilled water

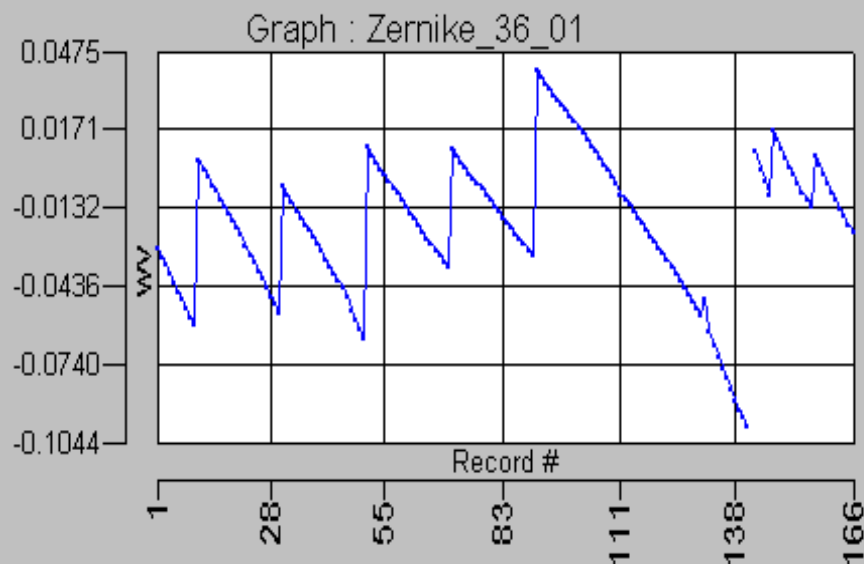
Disabled the LARGE volume fan in the airhandler and replaced it with a small household fan

Added a small household fan inside the tent to stir the air



# Stability before and after

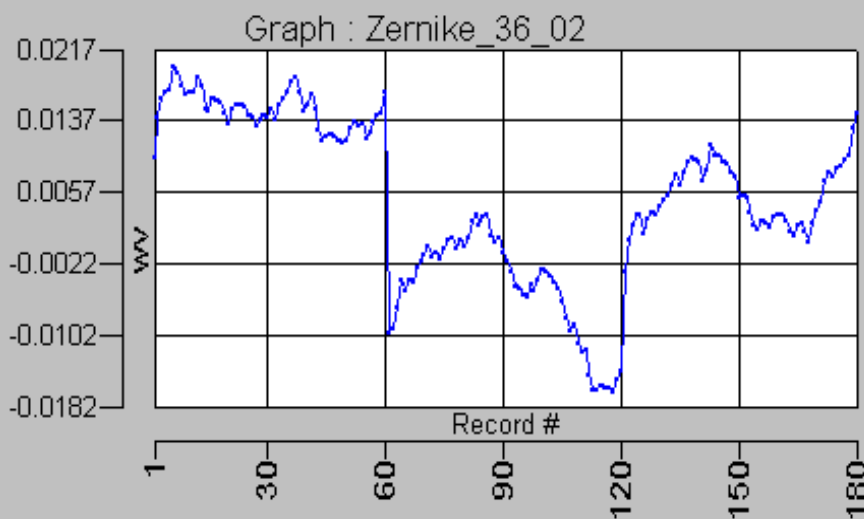
0.475 to  
-0.1044  
waves



Lab Temperature  
change

0.7 C°/day

0.0217 to  
-0.018  
waves



0.1 C° max



# Results

## Radius of Curvature

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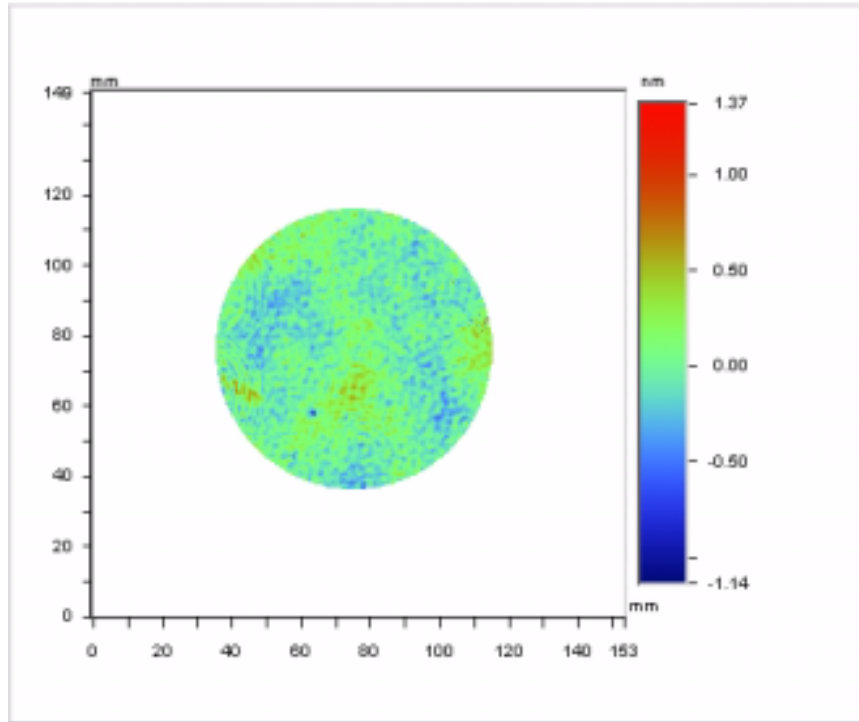
Measurement of Pathfinder piece A001 - 2 apertures

	<b>200 mm</b>	<b>150 mm</b>
<b>HDOS</b>	6.097 Km	
<b>CSIRO</b>	6.06 Km	6.08 Km
<b>CIT</b>		6.10 Km



# Results

## Surface errors (spec <0.8 nm)



Title: 4ITM06 zero degrees File name:  
 Note: Reference subtracted: Cflip6bcZ3 + Z4up from 10-10-00Avall

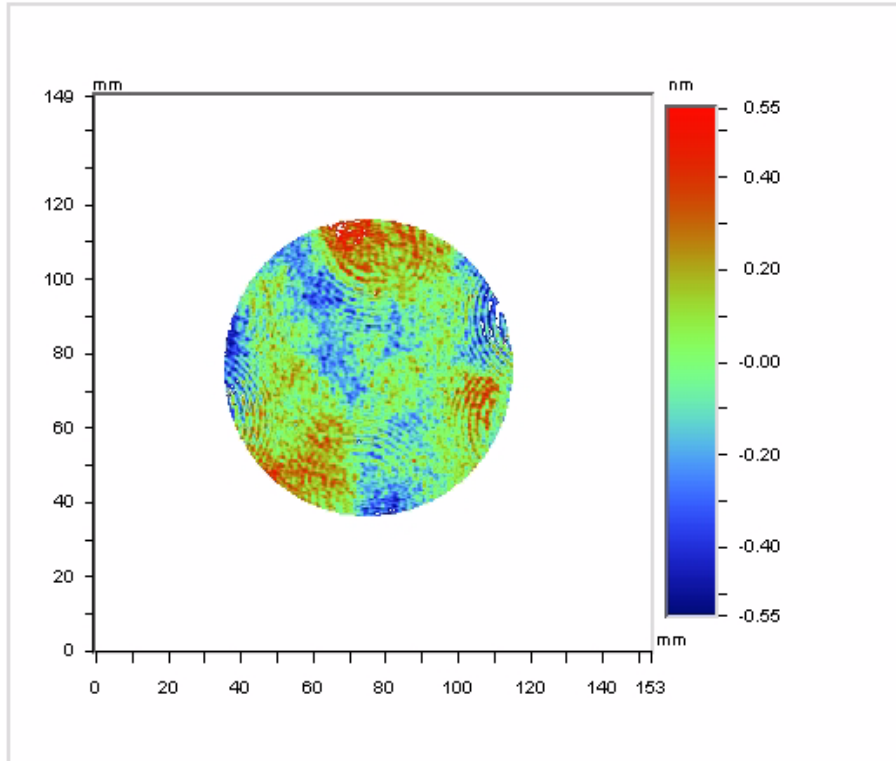
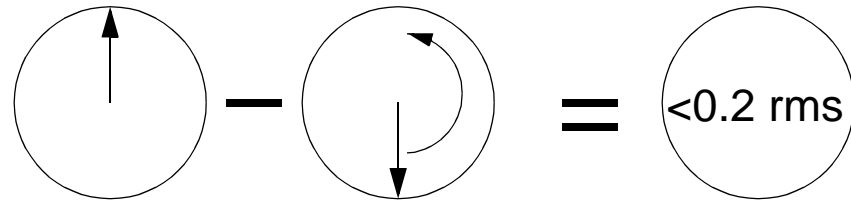
Zernike Coefficients	
Zernike_15[01]:	-0.030908 wv
Zernike_15[02]:	0.046024 wv
Zernike_15[03]:	0.026777 wv
Zernike_15[04]:	0.000070 wv
Zernike_8[1]:	-0.03091 wv
Zernike_15[05]:	0.000036 wv
Zernike_8[2]:	0.04602 wv
Zernike_15[06]:	-0.000010 wv
Zernike_8[3]:	0.02678 wv
Zernike_15[07]:	0.000103 wv
Zernike_8[4]:	0.00007 wv
Zernike_15[08]:	0.000072 wv
Zernike_8[5]:	0.00004 wv
Zernike_15[09]:	0.000093 wv
Zernike_8[6]:	-0.00001 wv
Zernike_15[10]:	-0.000028 wv
Zernike_8[7]:	0.00010 wv
Zernike_15[11]:	0.000117 wv
Zernike_8[8]:	0.00007 wv
Zernike_15[12]:	-0.000046 wv
Zernike_15[13]:	0.000001 wv
Zernike_15[14]:	-0.000039 wv
Zernike_15[15]:	-0.000022 wv

Date: 10/16/2000 X Center: 283.00  
 Time: 16:25:23 Y Center: 244.00  
 Wavelength: 1.064 um Radius: 150.00 pix  
 Pupil: 100.0 % Terms: Tilt Power Astig  
**PV: 2.5067 nm** Filters: None  
**RMS: 0.1639 nm** Masks: Analysis Mask  
 Rad of curv: 14.053 km Ref Sub: Averages:

Seidel Aberrations (8 Term Fit)			
	Coeff (per radius)	Rms	Angle
Tilt	0.0553 wv		124.0 deg
Power	0.0536 wv	0.015 wv	
Focus	0.0530 wv		
Astig	0.0002 wv	0.000 wv	0.0 deg
Coma	0.0003 wv	0.000 wv	0.0 deg
Sa3	0.0004 wv	0.000 wv	



# Repeatability



**Title: Difference** File name: Diff-4ITM06-0-180rot

Note:

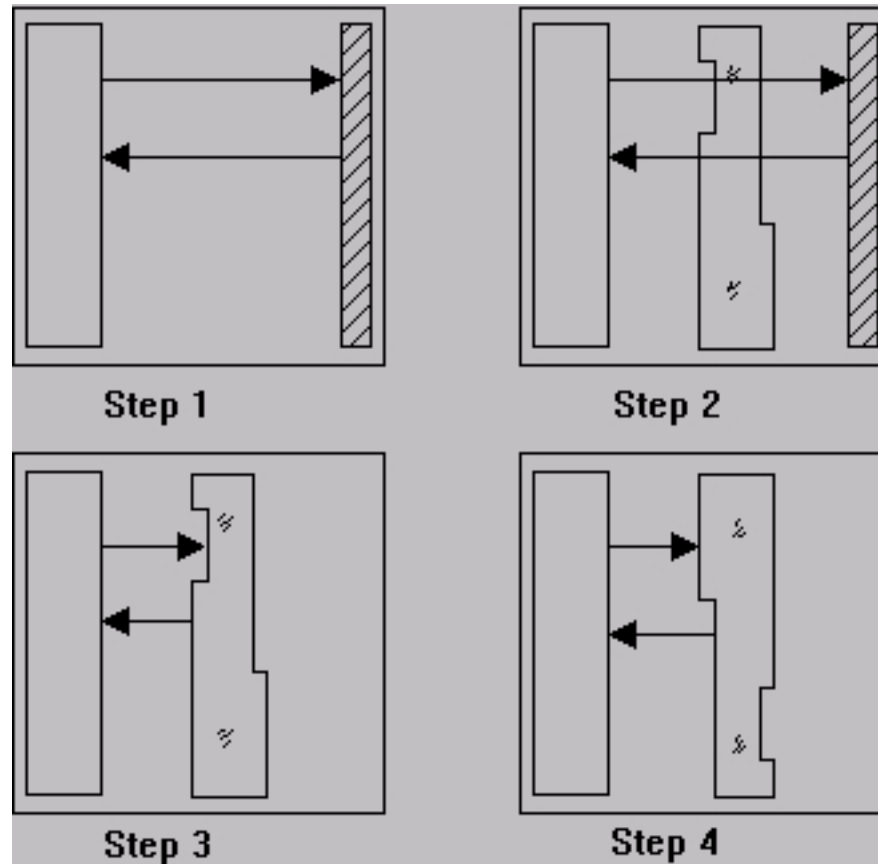
Zernike Coefficients	
Zernike_15[01]:	-0.056744 wv
Zernike_15[02]:	0.093147 wv
Zernike_15[03]:	0.000033 wv
Zernike_15[04]:	-0.000092 wv
Zernike_8[1]:	-0.05674 wv
Zernike_15[05]:	0.000071 wv
Zernike_8[2]:	0.09315 wv
Zernike_15[06]:	0.000007 wv
Zernike_8[3]:	0.000003 wv
Zernike_15[07]:	0.000047 wv
Zernike_8[4]:	-0.00009 wv
Zernike_15[08]:	-0.000071 wv
Zernike_8[5]:	0.00007 wv
Zernike_15[09]:	0.000066 wv
Zernike_8[6]:	0.00001 wv
Zernike_15[10]:	-0.000220 wv
Zernike_8[7]:	0.00005 wv
Zernike_15[11]:	-0.000068 wv
Zernike_8[8]:	-0.00007 wv
Zernike_15[12]:	-0.000060 wv
Zernike_15[13]:	0.000019 wv
Zernike_15[14]:	-0.000048 wv
Zernike_15[15]:	-0.000025 wv

Date: 10/17/2000 X Center: 283.00  
 Time: 11:25:35 Y Center: 244.00  
 Wavelength: 1.064 um Radius: 150.00 pix  
 Pupil: 100.0 % Terms: Tilt  
**PV: 1.0981 nm** Filters: None  
**RMS: 0.1782 nm** Masks: Analysis 3.0 Sigma Masks  
 Rad of curv: 11371.747 km Ref Sub: Averages:

Seidel Aberrations (8 Term Fit)			
	Coeff (per radius)	Rms	Angle
Tilt	0.1090 wv		121.4 deg
Power	0.0001 wv	0.000 wv	
Focus	0.0004 wv		
Astig	0.0002 wv	0.000 wv	0.0 deg
Coma	0.0001 wv	0.000 wv	0.0 deg
Sa3	-0.0004 wv	0.000 wv	

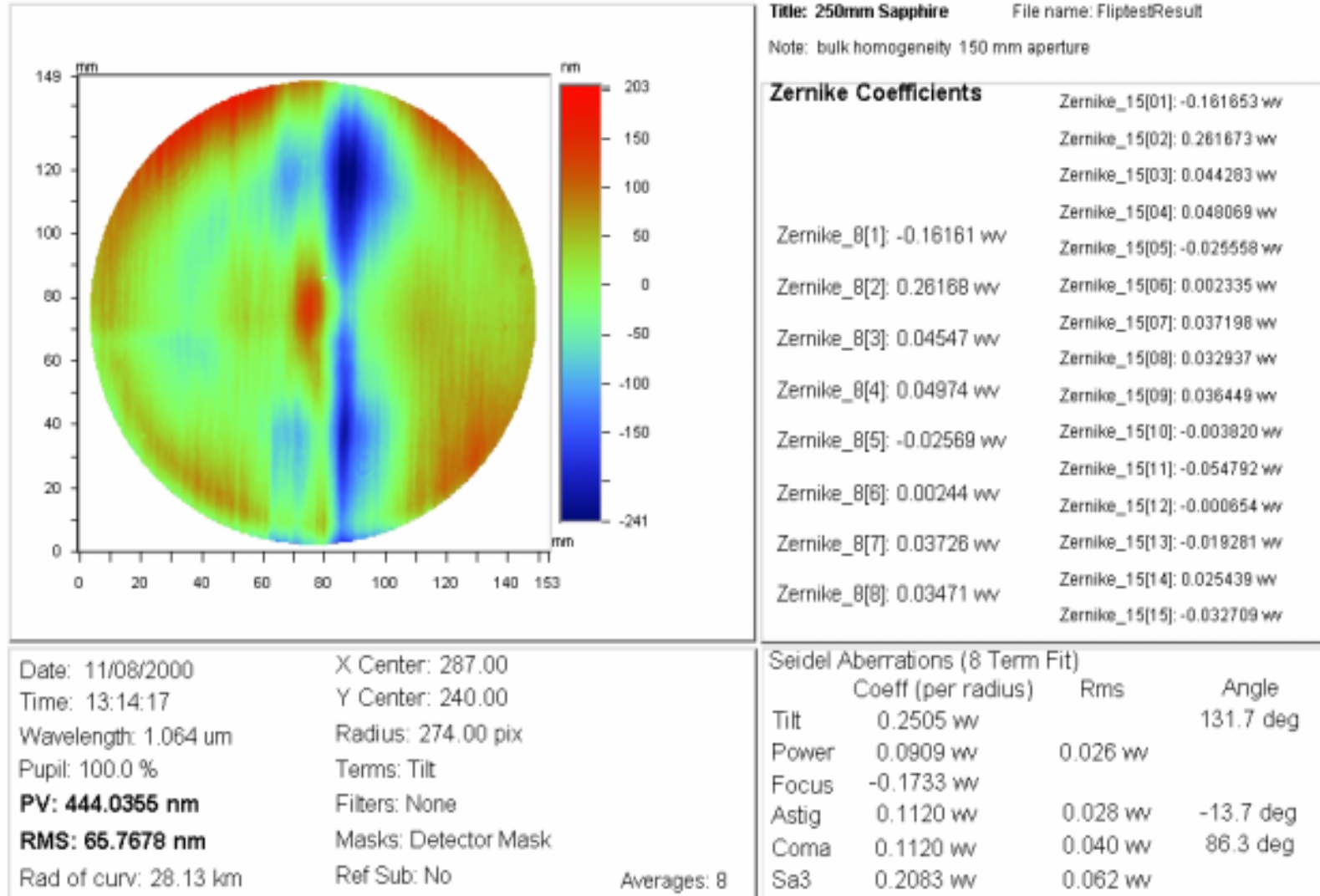


# Homogeneity Measurement “Flip” method





# Homogeneity Measurement of 25 cm Sapphire substrate







## Coming Soon

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Measurement of small ROC (40 meter optics)

Transmission measurements of Sapphire

Calibration Study