Deep Nulling in with Broadband Visible Light

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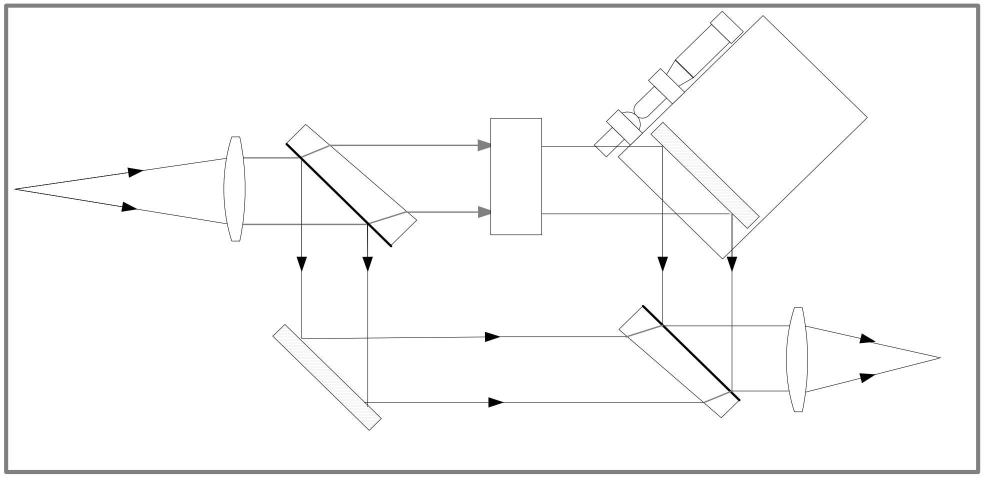
1 JPL
2 NGST

Experimental Goals

- 10^{-10} scattered light level implies ~10^{-7} suppression of starlight per mode
  - This assumes a 1000 element single mode fiber array and
  - Residual leakage from any fiber in the array is incoherent with the other fibers in the array
- *Our goal is to demonstrate a null of 10^{-7} over a 20% BW centered at 675 nm.*

Quick Nulling Interferometry Review



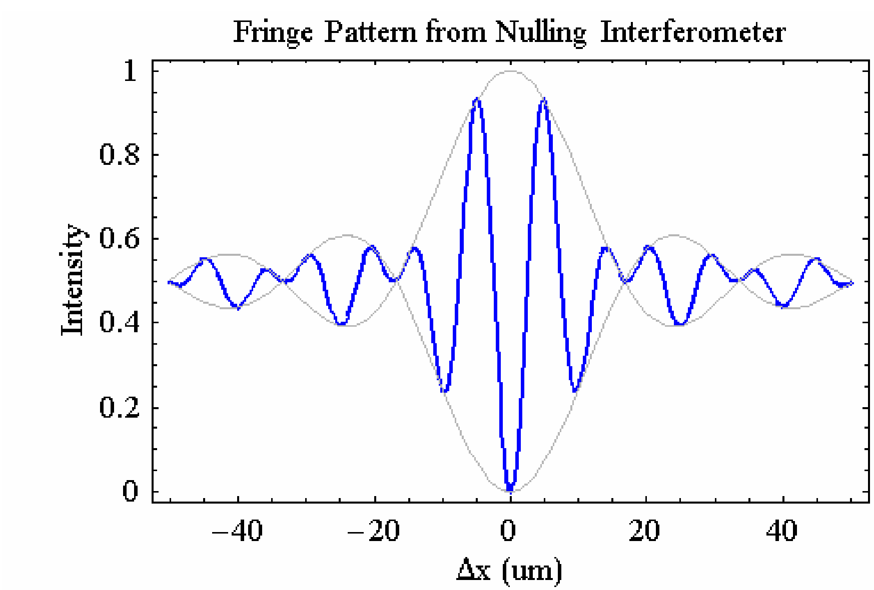
Nulling Interferometer

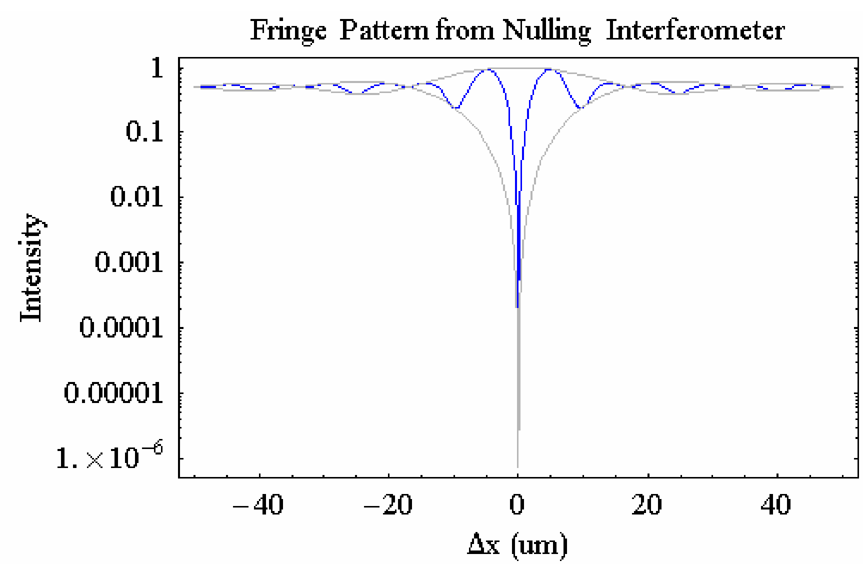
Achromatic!

$$I(\Delta x) = \frac{Io}{2}\left[1 + Cos(\frac{2\pi}{\lambda}\Delta x + \pi)\right]$$

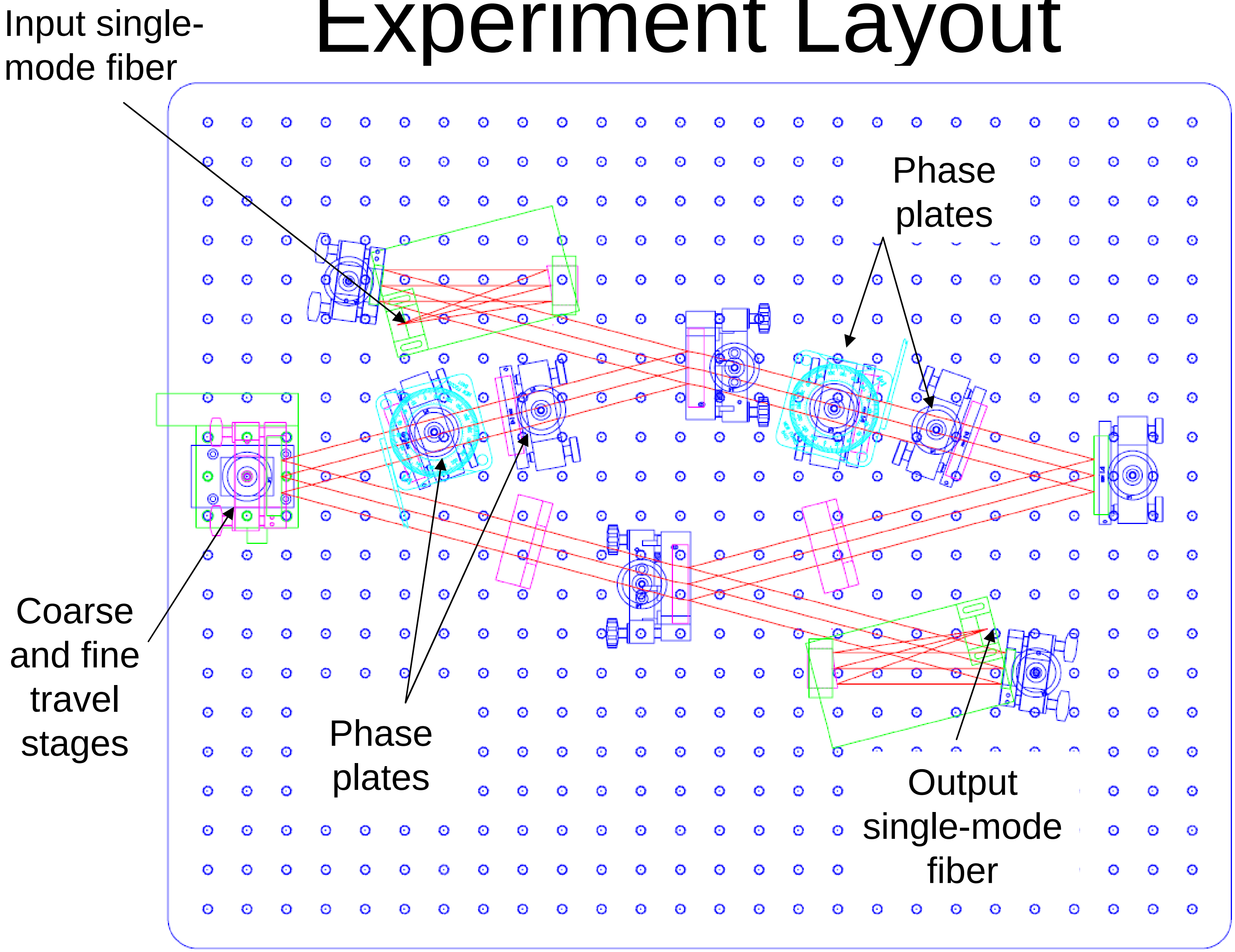
$$I(\Delta x) = \frac{Io}{2}\left[1 - Cos(\frac{2\pi}{\lambda}\Delta x)\right]$$

$$\varphi(\lambda) = \sum_i \frac{2\pi}{\lambda} n_i(\lambda) t_i = \pi$$

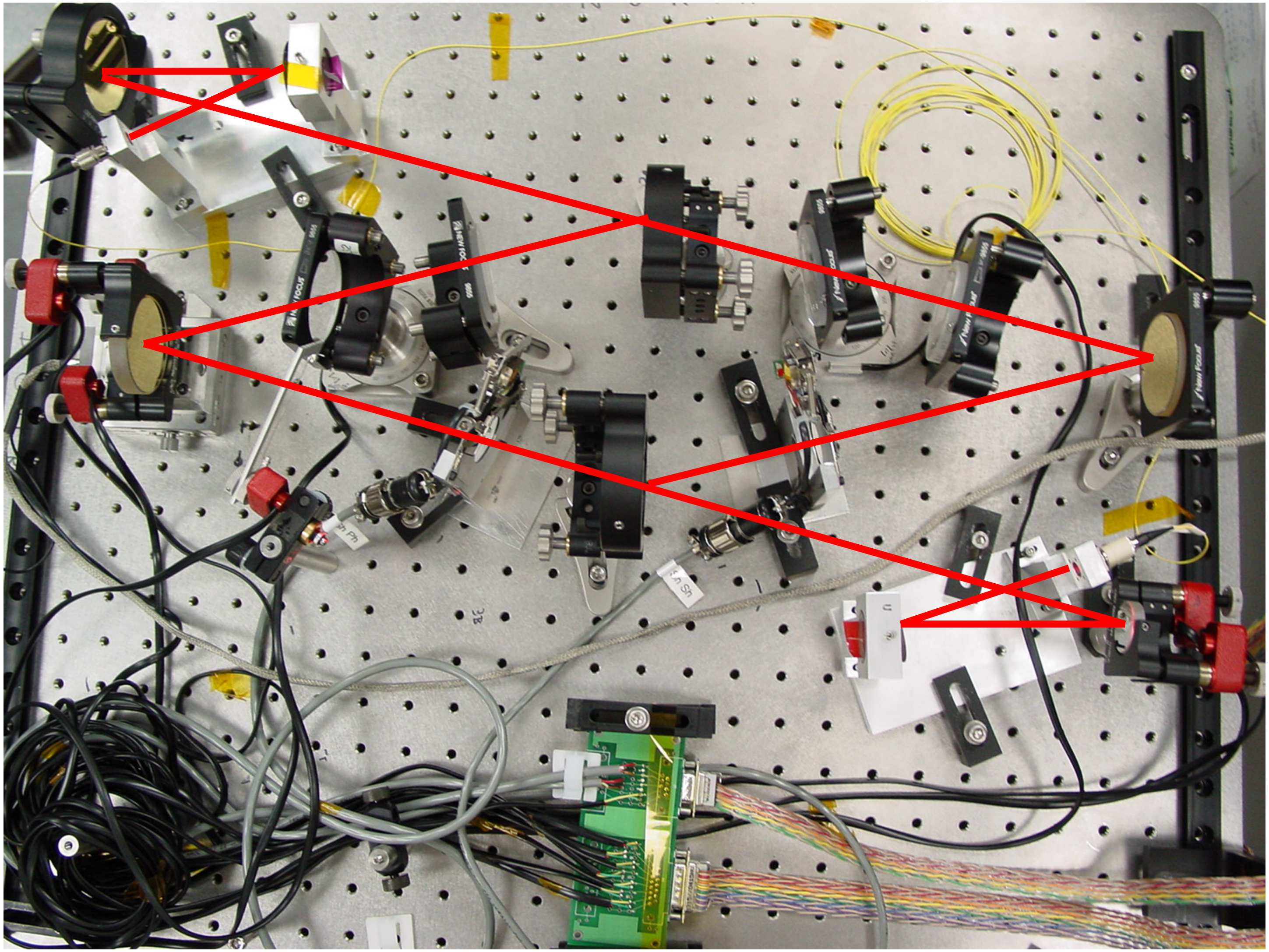




Experiment Layout



Experiment Hardware

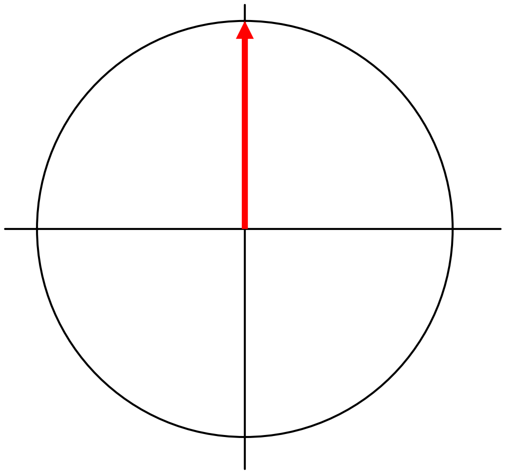


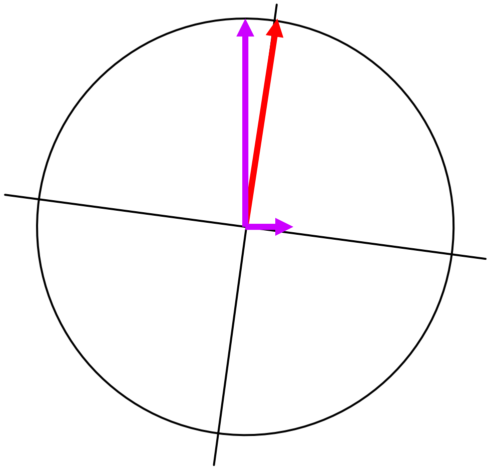
Error Budget

	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	θ	ΔI, %	ΔOPD	$\Delta OPD,_{pol}$	$\Delta OPD,_{\lambda}$
Null Limit	$\Theta^2/4$	$\Delta I^2/4$	$(2\pi \Delta OPD/\lambda)^2/4$	$(2\pi \Delta OPD,_{pol} /\lambda)^2/16$	$(2\pi \Delta OPD,_{\lambda} / \lambda)^2/4$
Net Null:	$\Sigma = \Theta^2/4 + \Delta I^2/4 + (2\pi \Delta OPD/\lambda)^2/4 + (2\pi \Delta OPD,_{pol} /\lambda)^2/16 + (2\pi \Delta OPD,_{\lambda} / \lambda)^2/4$				
% Contribution	$\Theta^2/4/ \Sigma$	$\Delta I^2/4/ \Sigma$	$(2\pi \Delta OPD/\lambda)^2/4/ \Sigma$	$(2\pi \Delta OPD,_{pol} /\lambda)^2/16/ \Sigma$	$(2\pi \Delta OPD,_{\lambda} / \lambda)^2/4/ \Sigma$

Pupil Rotation

- Strictly a geometric effect:
  - Out of plane folds create slight pupil rotations.
  - Causes a small component of one polarization to 'leak' into the other polarization.
- Corrected by a very careful initial alignment of the interferometer
  - Use an interferometer to align an interferometer



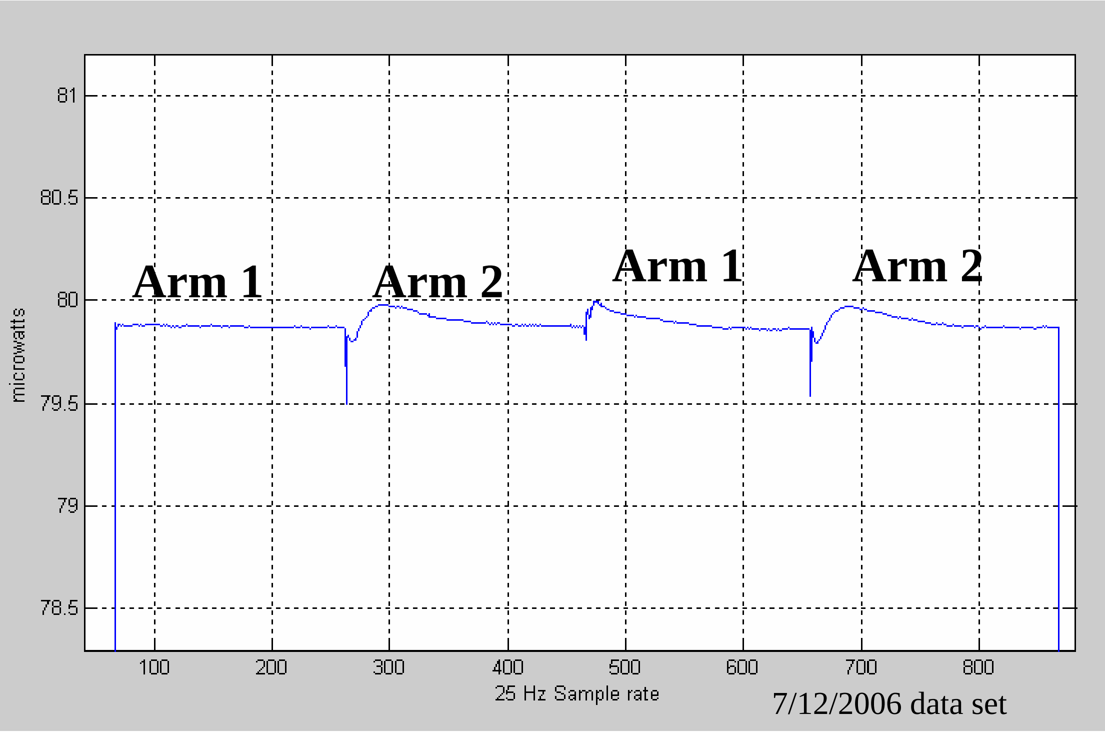


Error Budget:
Pupil Rotation

	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg				
Null Limit	7.6E-9				
Net Null:	7.6E-9 (132M:1)				
% Contribution	100 %				

Intensity Balance

- Accomplished with a wire that slightly occults the beam in one arm.
- Each arm is averaged over 3 seconds, allowing for heat dissipation.
- This set yields an imbalance of 0.009% and 0.008%
- Maintaining this level of balance is a challenge

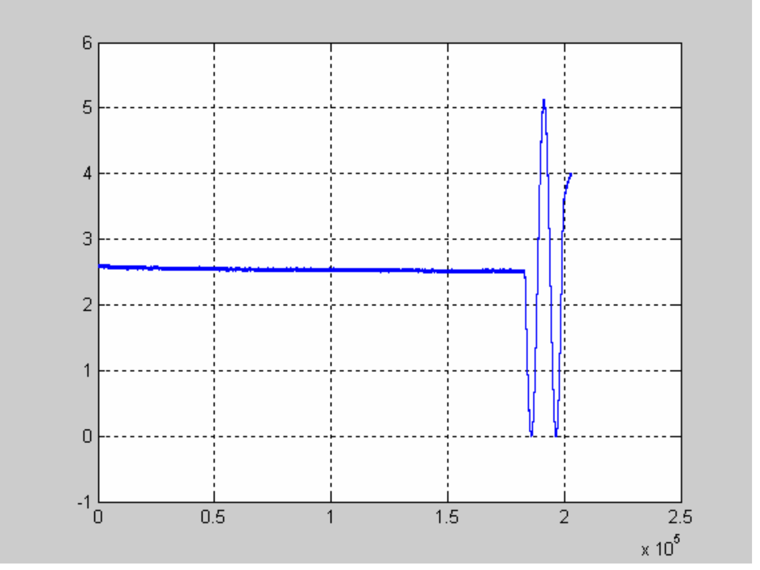


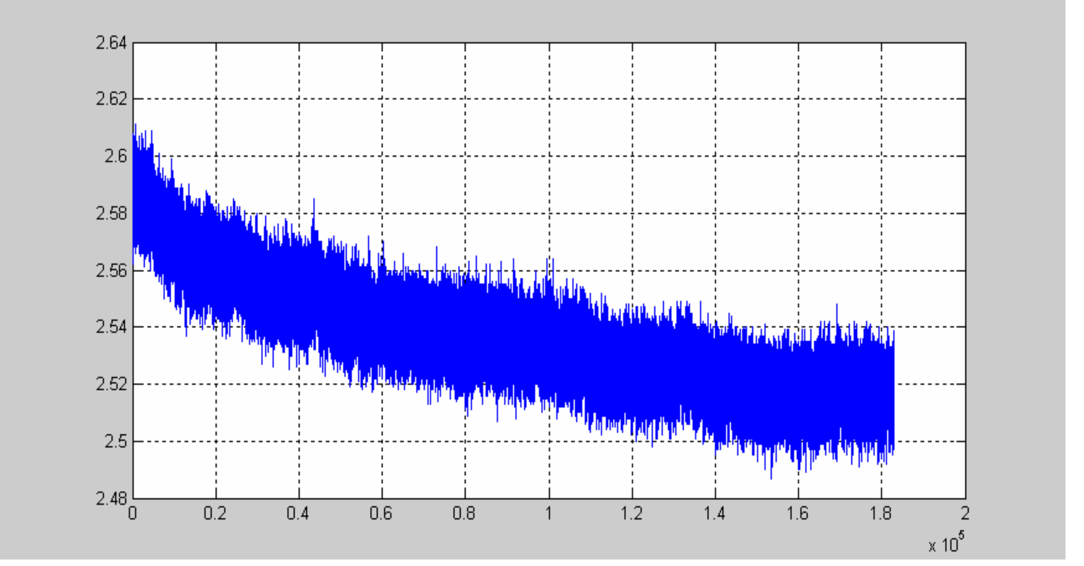
Error Budget:

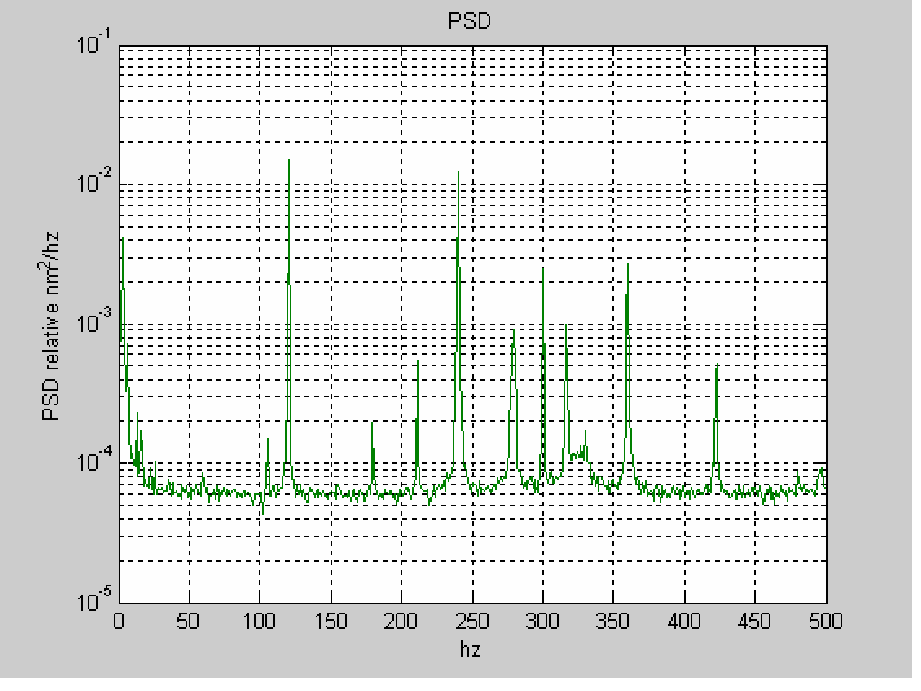
Pupil Rotation
Intensity Balance

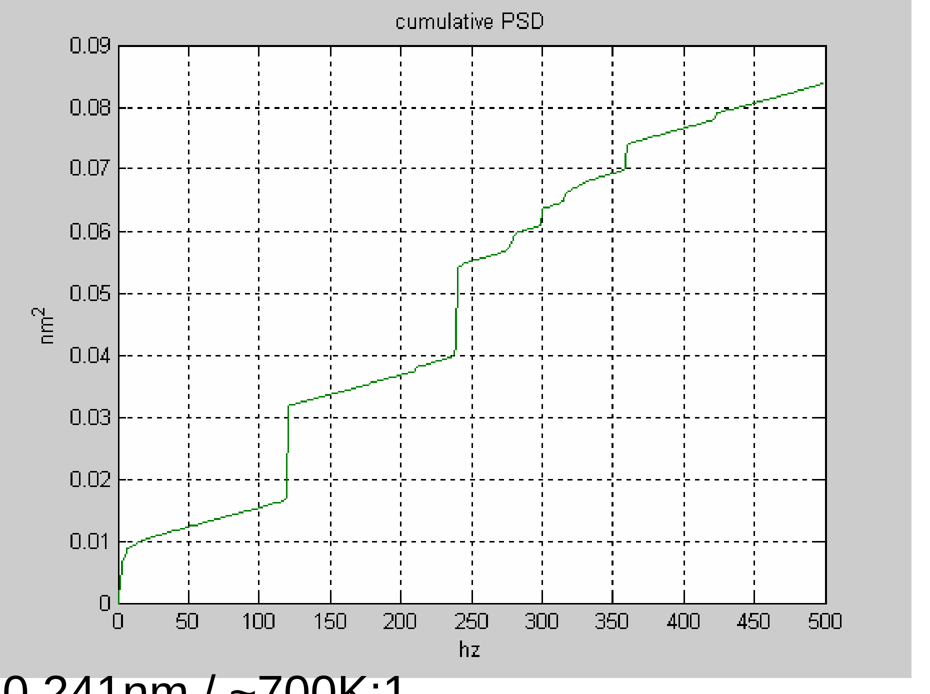
	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg	0.03%			
Null Limit	7.6E-9	2.25E-8			
Net Null:	3.01E-8 (33M:1)				
% Contribution	25.3%	74.7%			

Pathlength Control







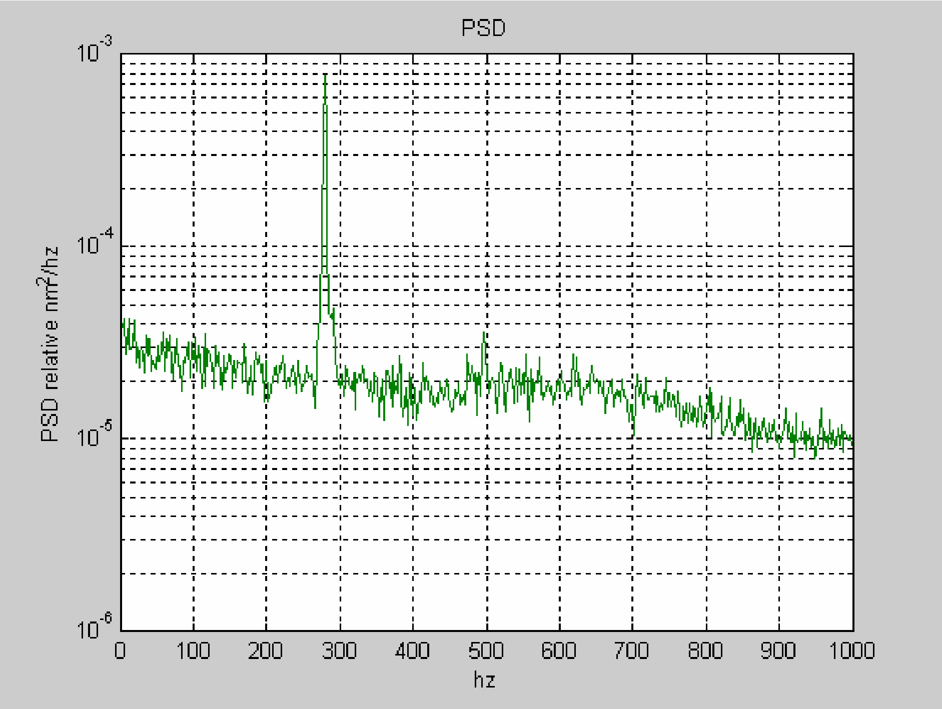


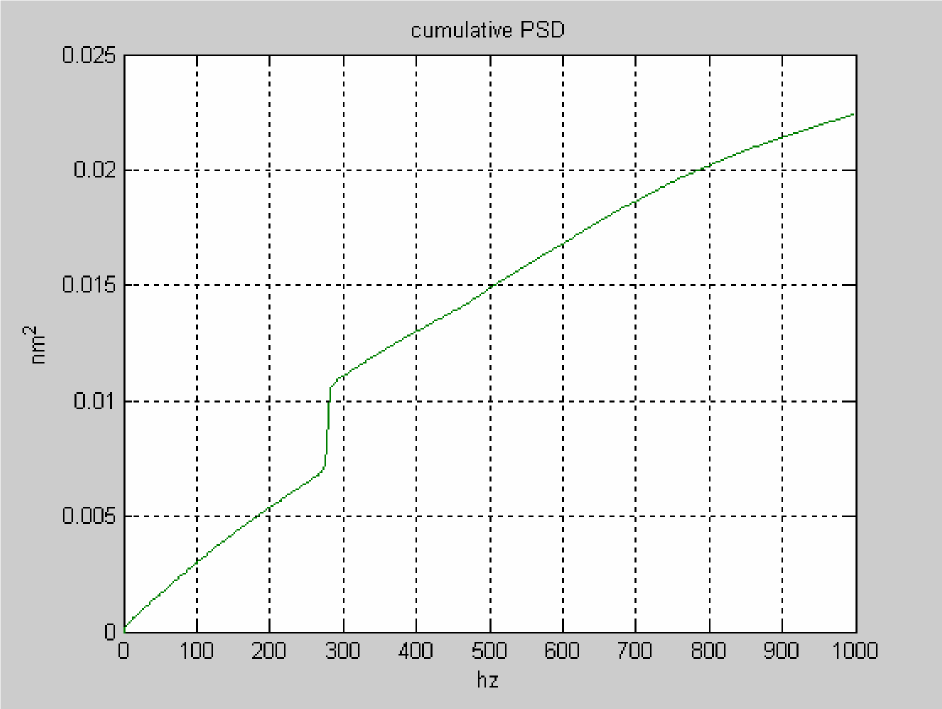
0.241nm / ~700K:1

Midfringe – Set 11 – 2khz

8/2/2006 - condtions: new focus detector, sampling at 2Khz, Edouard's potentiometer for fine voltage adjustment of the pzt is connected to the analog in. the chamber has been closed at least overnight

Data recorded 1 day after slide 1's midfringe





Similar, but the noise level has decreased.

~9 Million limit

Error Budget:

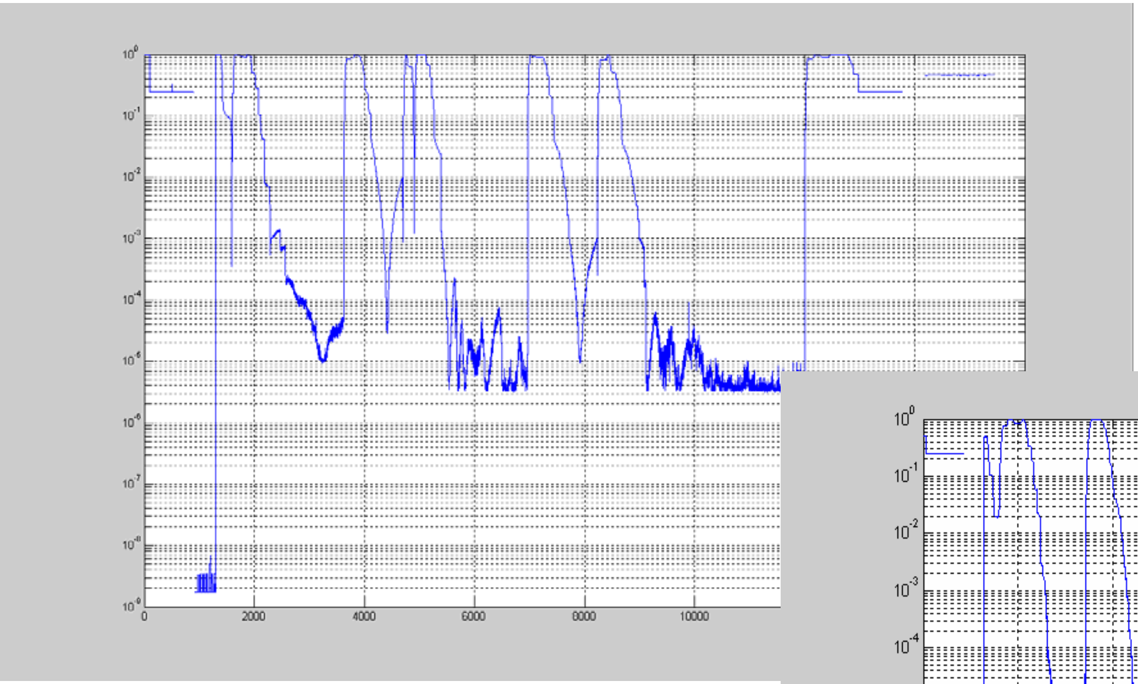
Pupil Rotation
Intensity Balance
Pathlength Control

	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg	0.03%	0.06 nm, rms		
Null Limit	7.6E-9	2.25E-8	8.73E-8		
Net Null:	1.17E-7 (8.5M:1)				
% Contribution	6.5%	19.2%	74.3%		

Birefringence (Stress-Induced)

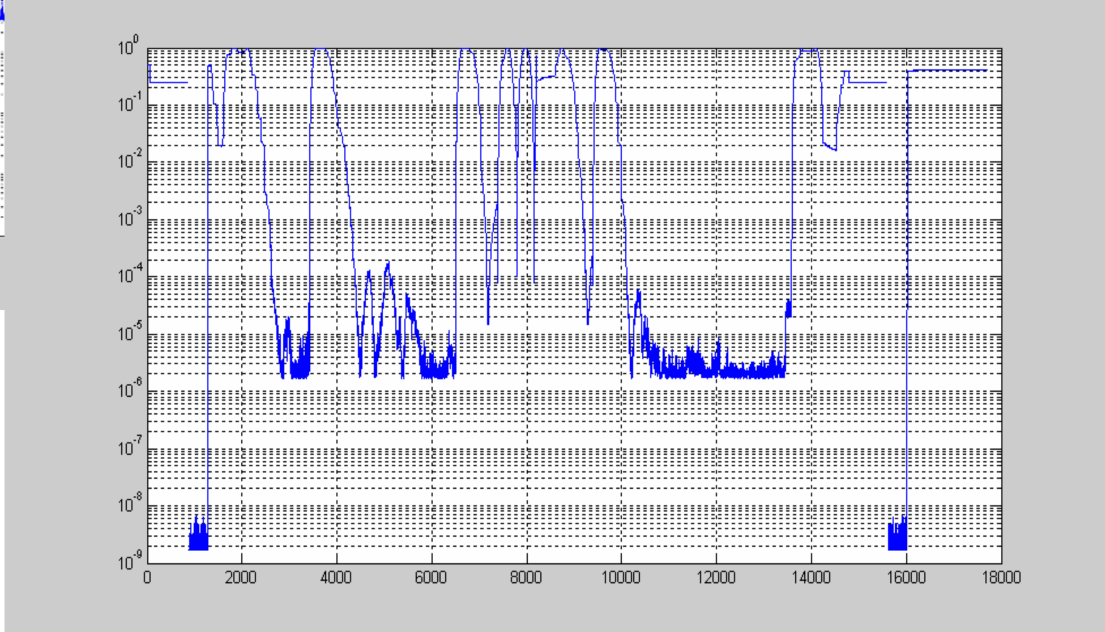
Evidence of Birefringence

Phase Plates In



Null = 260K:1 Over 4 seconds

Phase Plates Out



Null = 520K:1

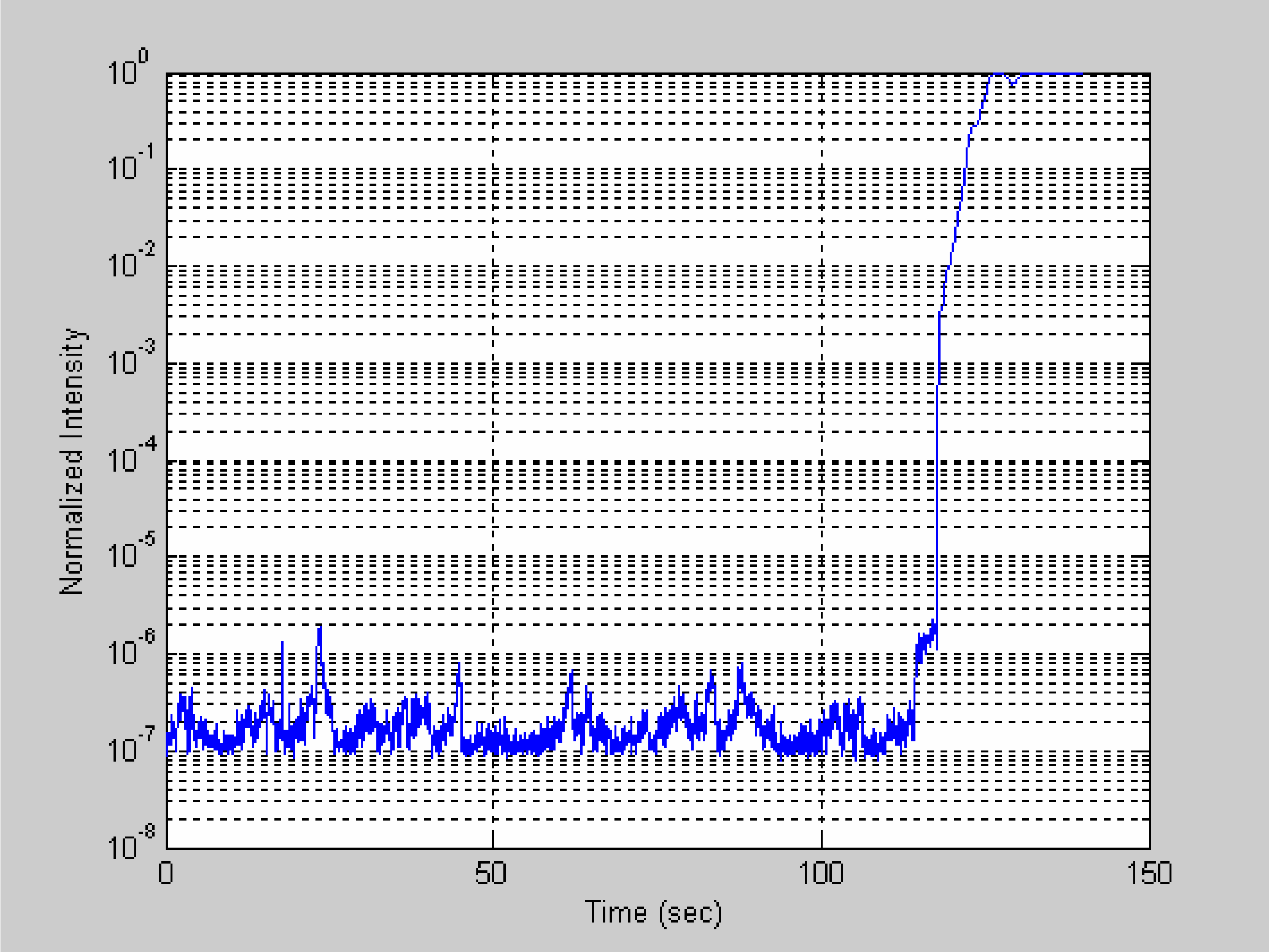
Error Budget:

Pupil Rotation
Intensity Balance
Pathlength Fluctuations
Birefringence

	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg	0.03%	0.06 nm, rms	0.04 nm	
Null Limit	7.6E-9	2.25E-8	8.73E-8	9.7E-9	
Net Null:	1.27E-7 (7.9M:1)				
% Contribution	6.0%	17.7%	68.7%	7.6%	

Deep Nulling of Laser Light

- 9M:1 over 3 seconds and 8M:1 over 10 secs

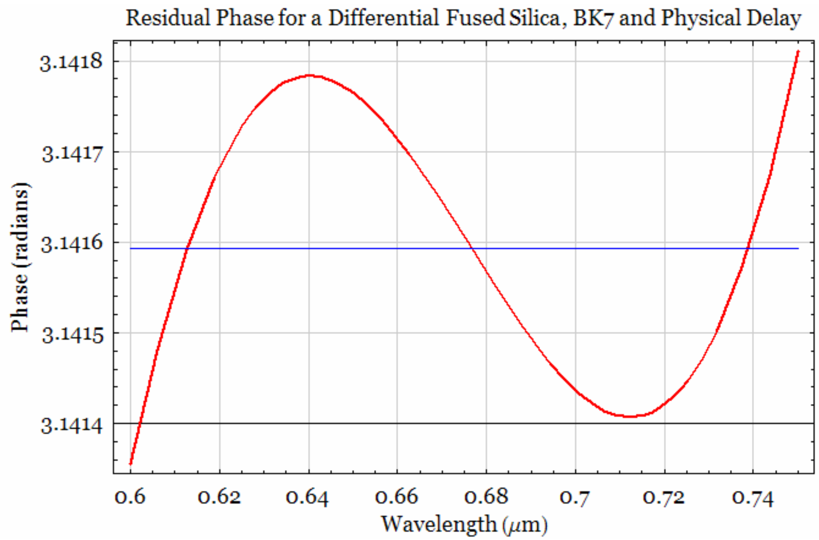


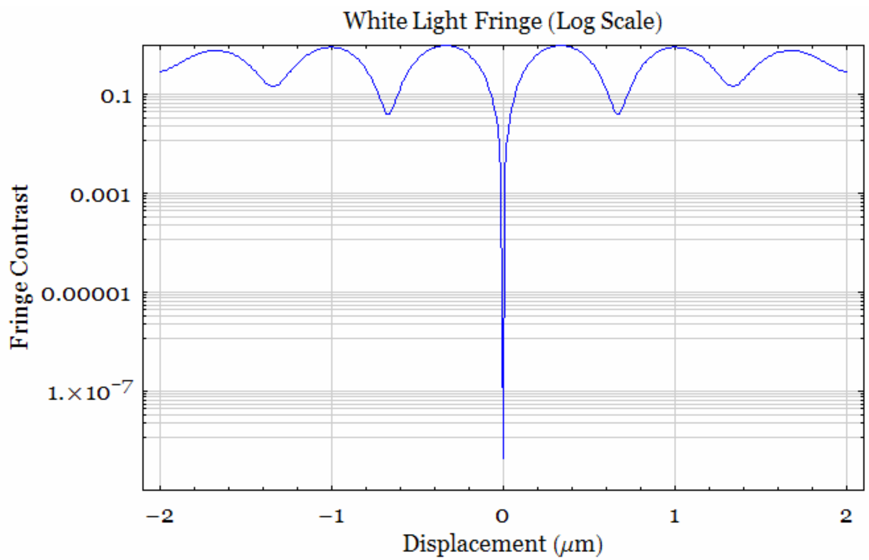
Error Budget:

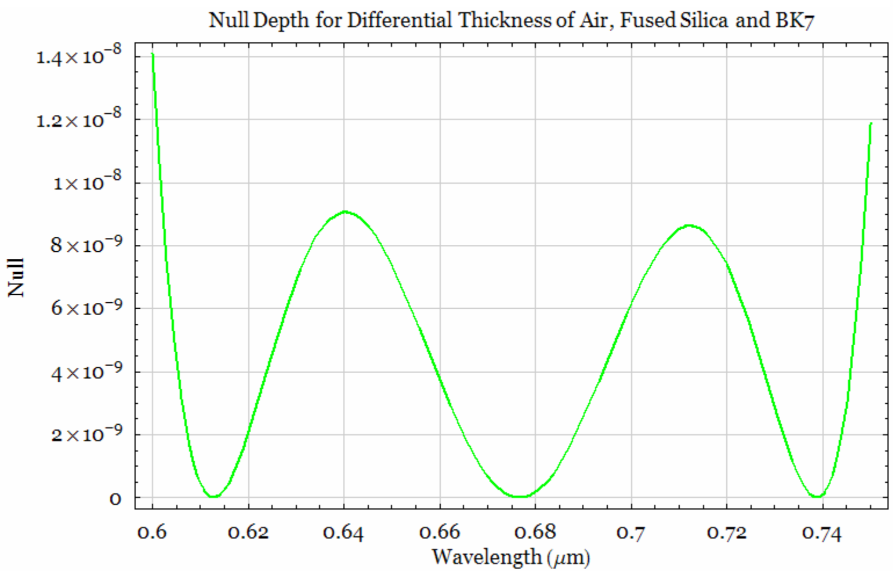
Pupil Rotation
Intensity Balance
Pathlength Fluctuations
Birefringence

	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg	0.03%	0.06 nm, rms	0.04 nm	**??**
Null Limit	7.6E-9	2.25E-8	8.73E-8	9.7E-9	**??**
Net Null:	1.27E-7 (7.9M:1)				
% Contribution	6.0%	17.7%	68.7%	7.6%	

Nulling with Phase Plates: Differential BK7, Fused Silica and Air



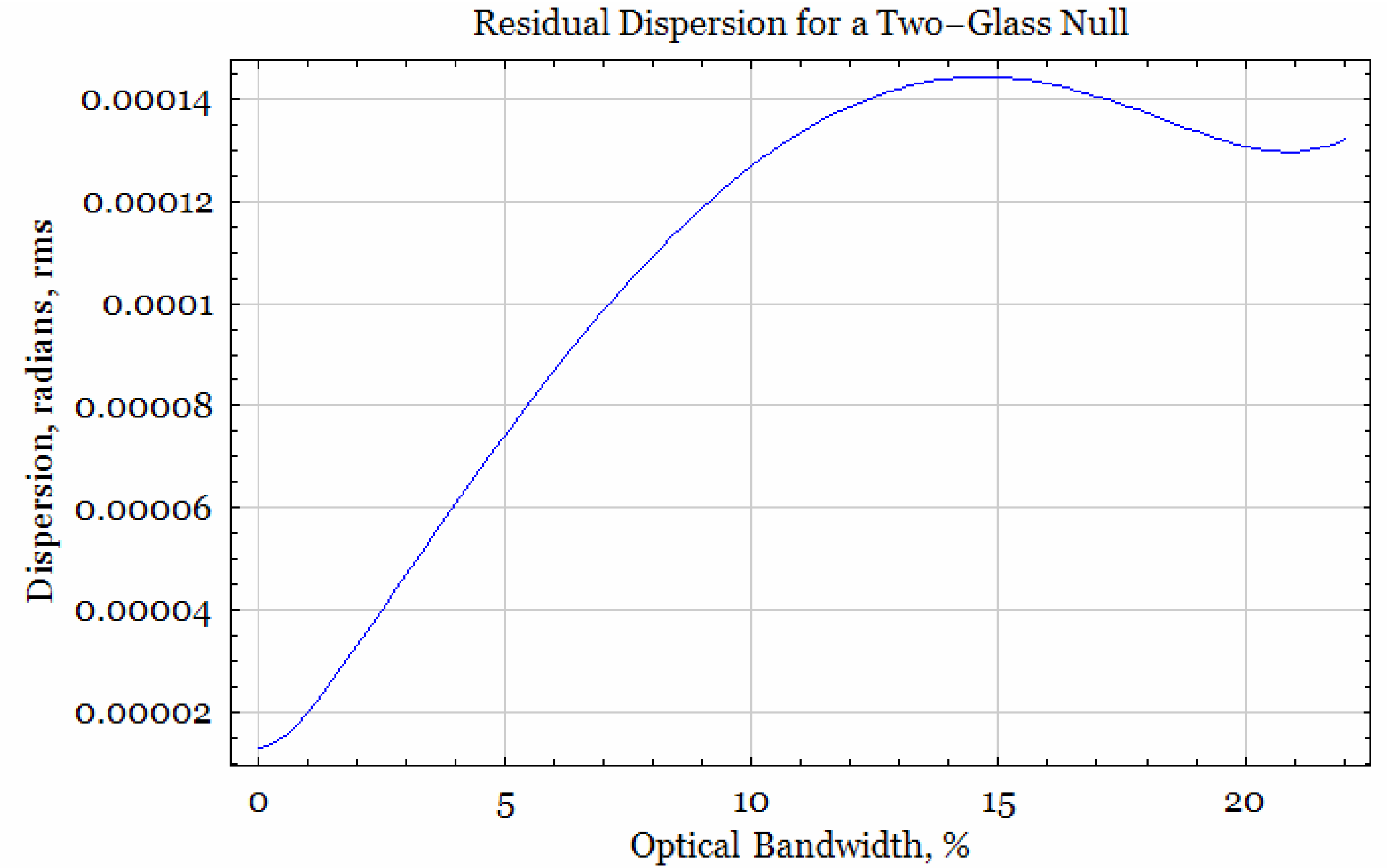


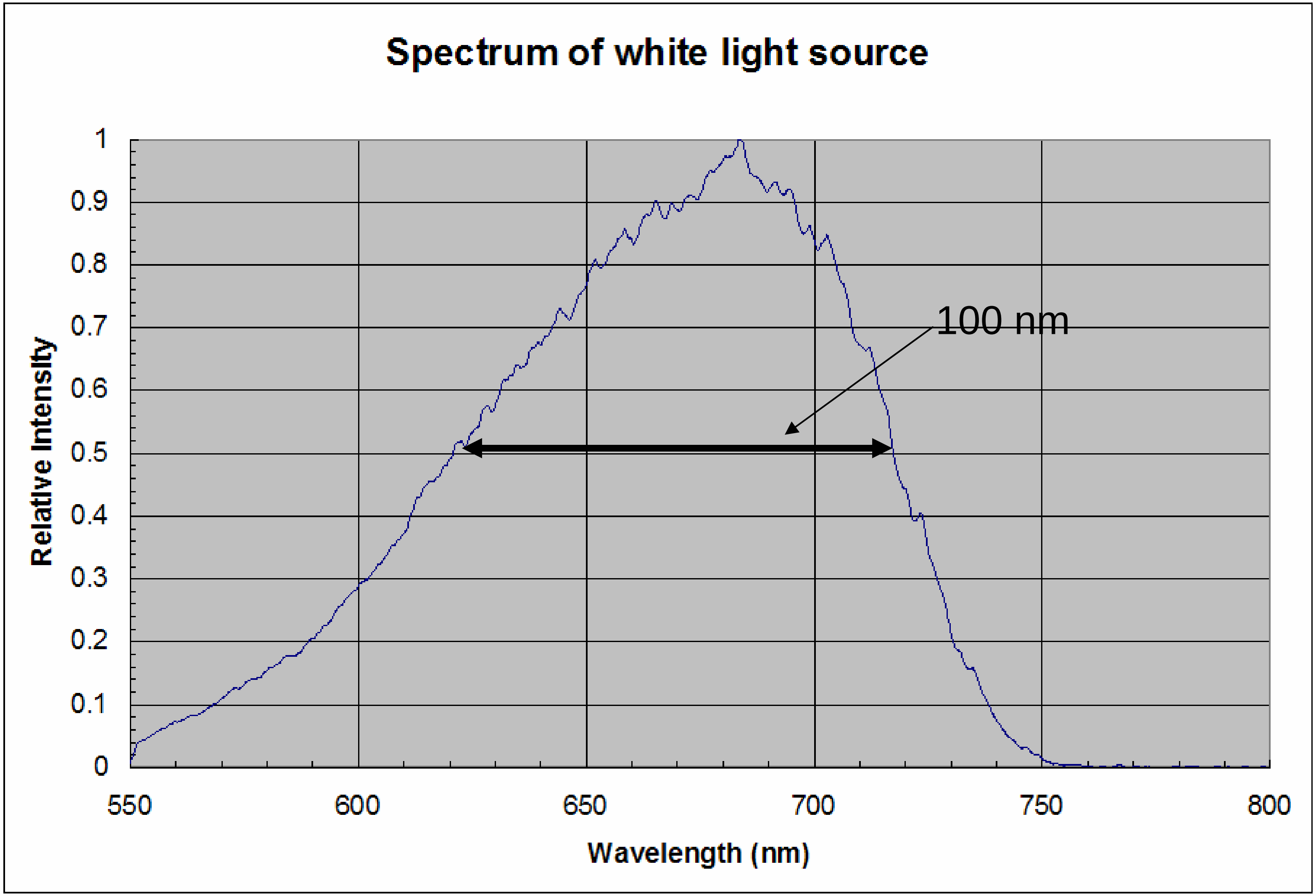


Average Null = 225M:1

Lambda = 600 – 750 nm

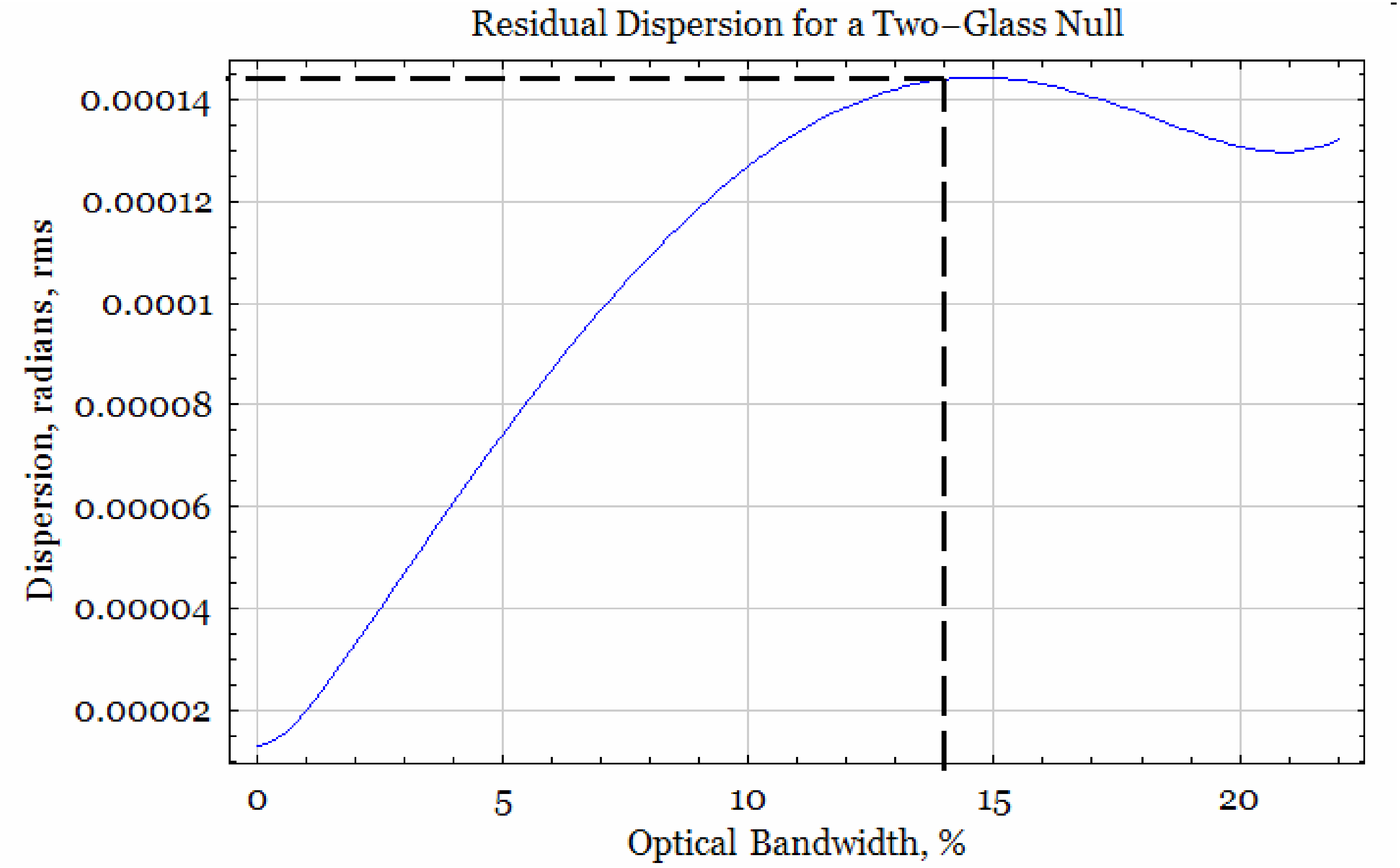
Residual Dispersion vs Bandwidth





Bandwidth = 14-15%

Residual Dispersion vs Bandwidth



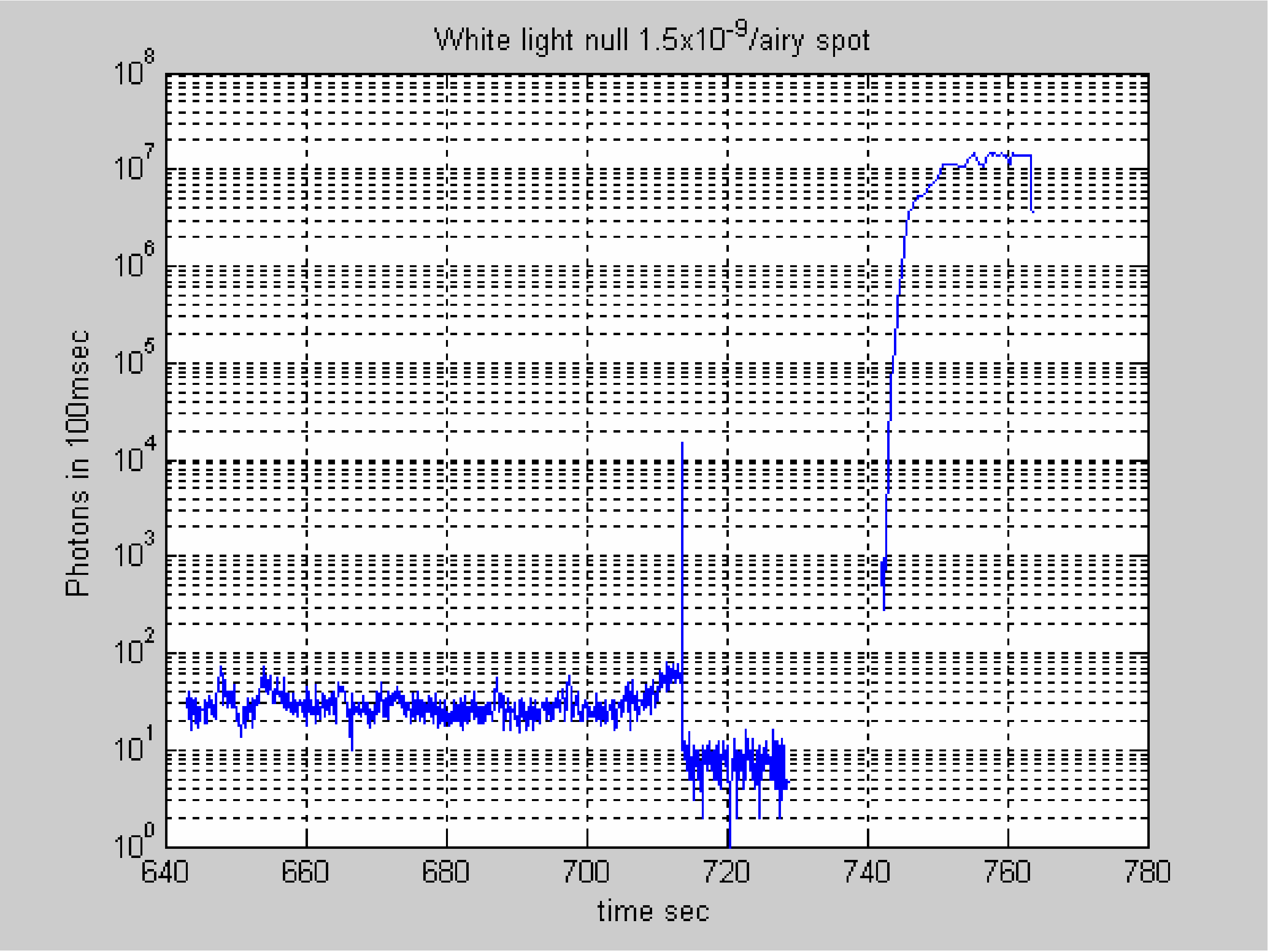
Error Budget:

Pupil Rotation
Intensity Balance
Pathlength Fluctuations
Birefringence
Dispersion

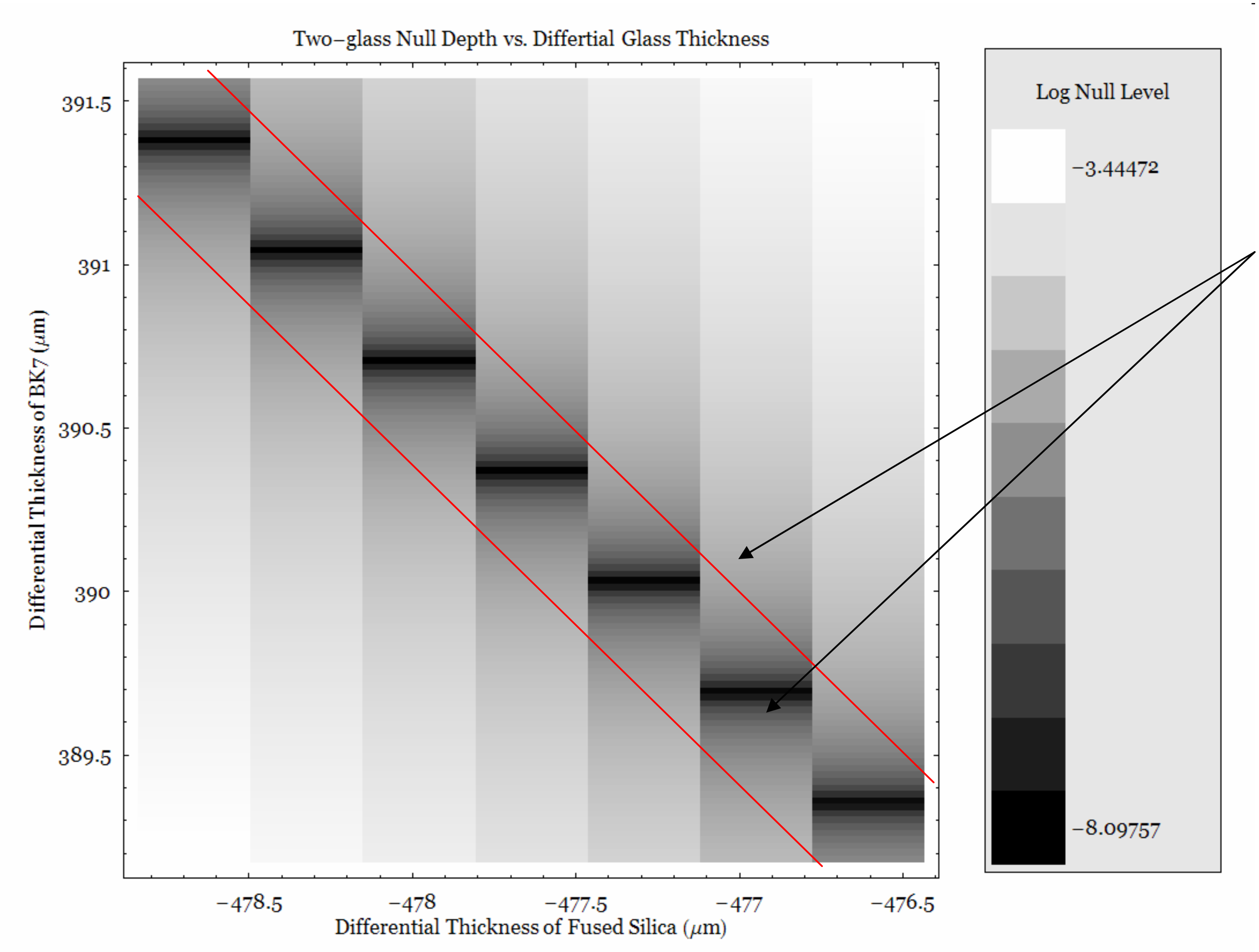
	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg	0.03%	0.06 nm, rms	0.04 nm	0.014 nm
Null Limit	7.62E-9	2.25E-8	8.73E-8	9.70E-9	4.89E-9
Net Null:	1.32E-7 (7.6M:1)				
% Contribution	5.8%	17.0%	66.1%	7.4%	3.7%

Broadband Results

- 1.05E-6 over 3 seconds



Why the disconnect?



$$\delta T_{BK7} = \pm 150\ nm$$

Adjusting the differential glass to this tolerance is easy!

Equivalent to about 10 resolution elements.

Modified Error Budget:

Pupil Rotation

Intensity Balance

Pathlength Fluctuations

Birefringence

Dispersion

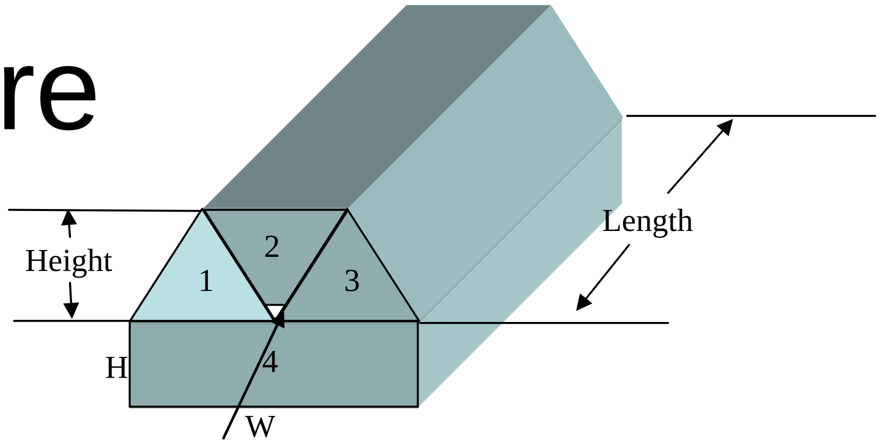
	Easy		Moderate		Challenging
Source / Null	**Pupil Rotation**	**Intensity Mismatch**	**OPD Fluctuations**	**Birefringence**	**Dispersion**
Value	0.01 Deg	0.1%	0.1 nm, rms	0.04 nm	0.15 nm
Null Limit	7.62E-9	2.5E-7	2.42E-7	9.70E-9	4.89E-9
Net Null:	1.06E-6 (950K:1)				
% Contribution	1%	24%	23%	1%	51%

Is this the answer?
It's going to take some more measurements to know.

Summary of results

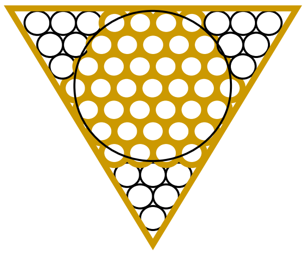
- We have a very accurate error budget that predicts (pretty well) our nulling performance and guides our experimental efforts.
- We have demonstrated dispersion control to nulling levels of at least 1E-6 over 15% BW for a single mode.
- Path length fluctuations will limit us to about 1E-7 per single mode.
  - With a 1000 element single mode fiber array used as a pupil filter, this equivalent to 1E-10 per air spot.

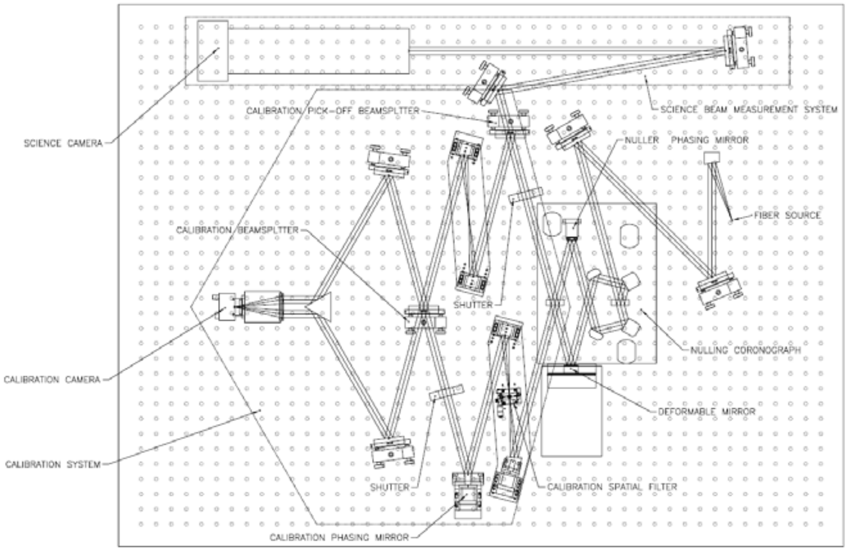
Future



- Full imaging mode:
  - Fiber bundle array.
  - Calibration system.

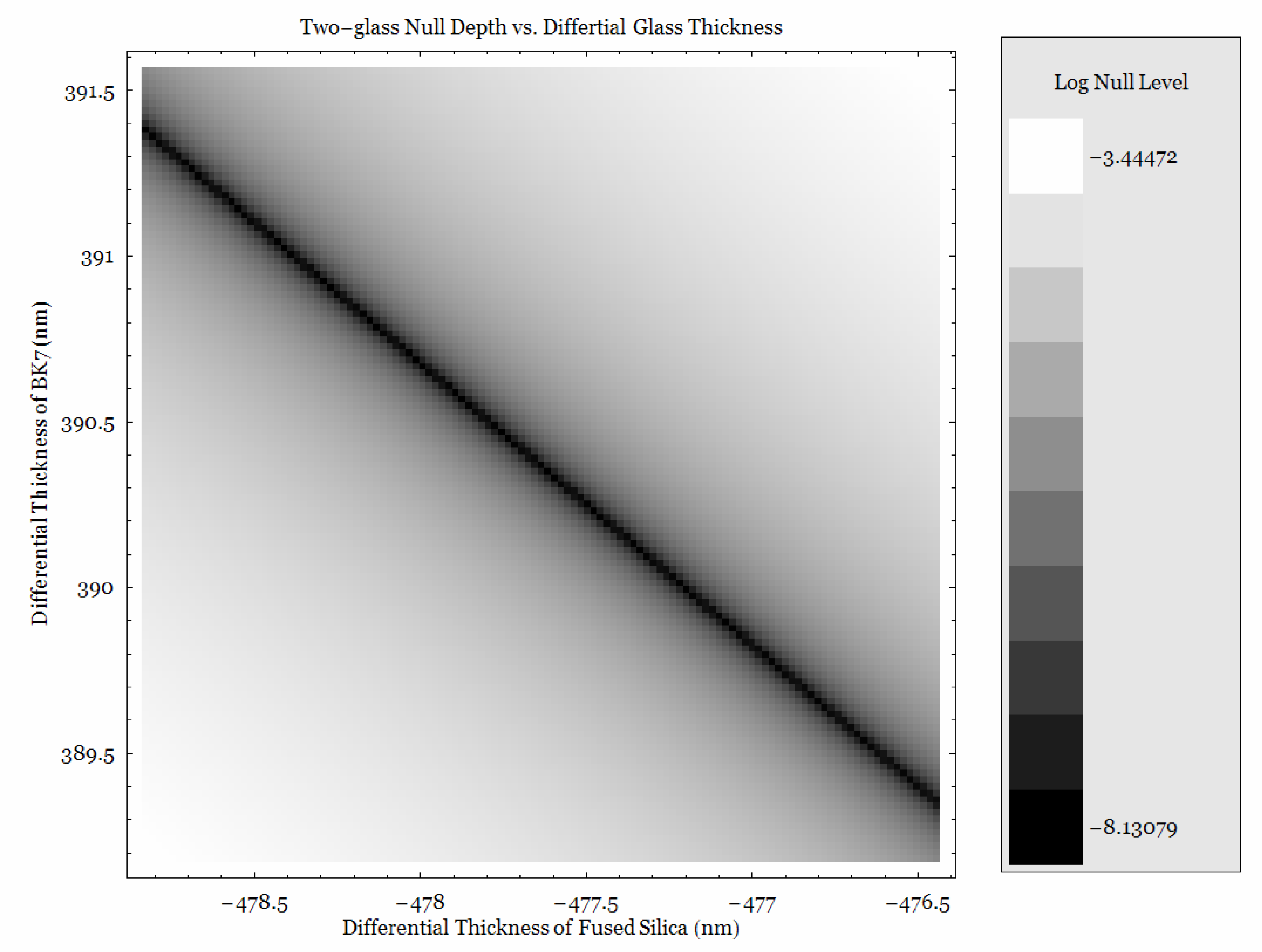
•Fiber Array Detail



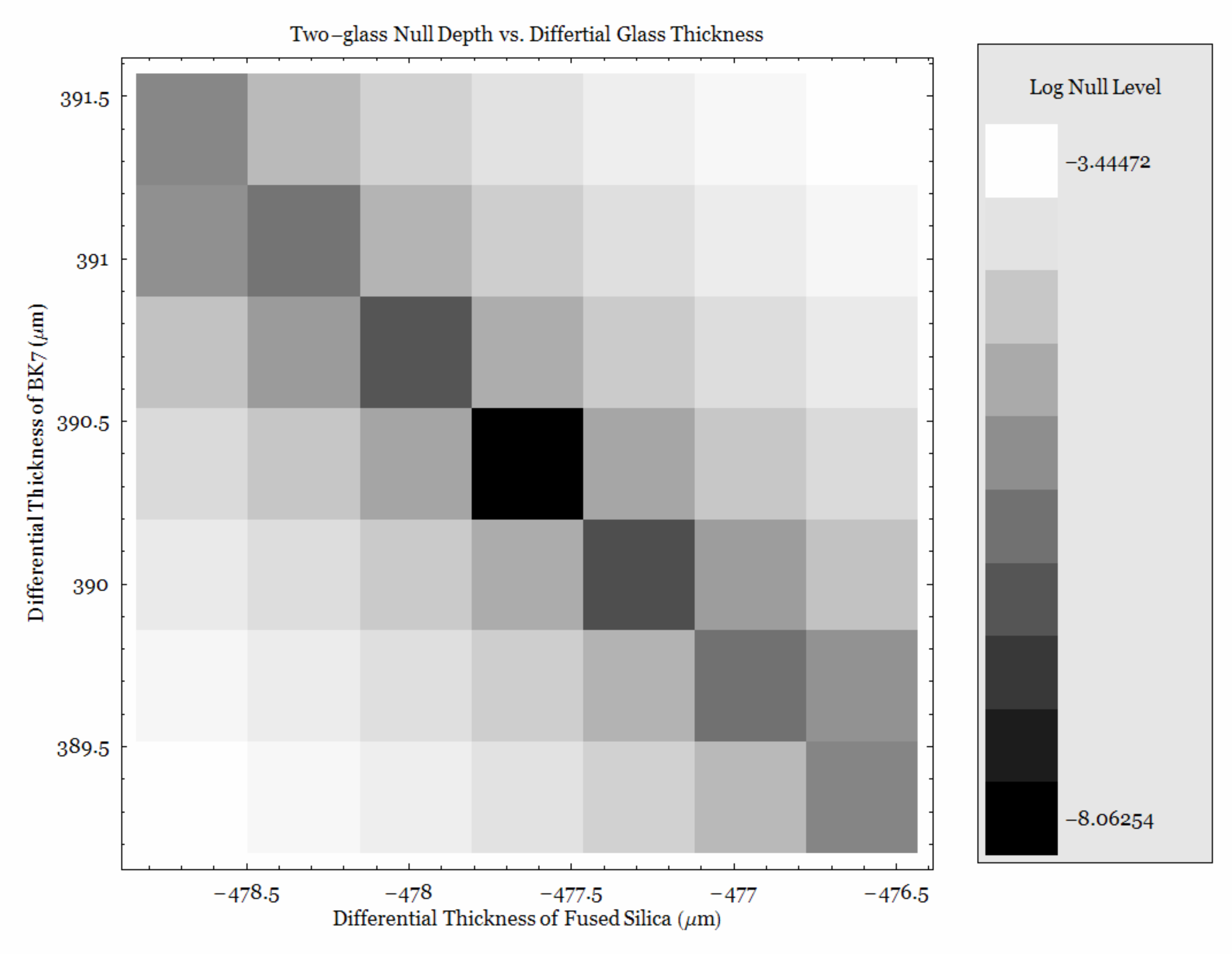


Back Up Slides

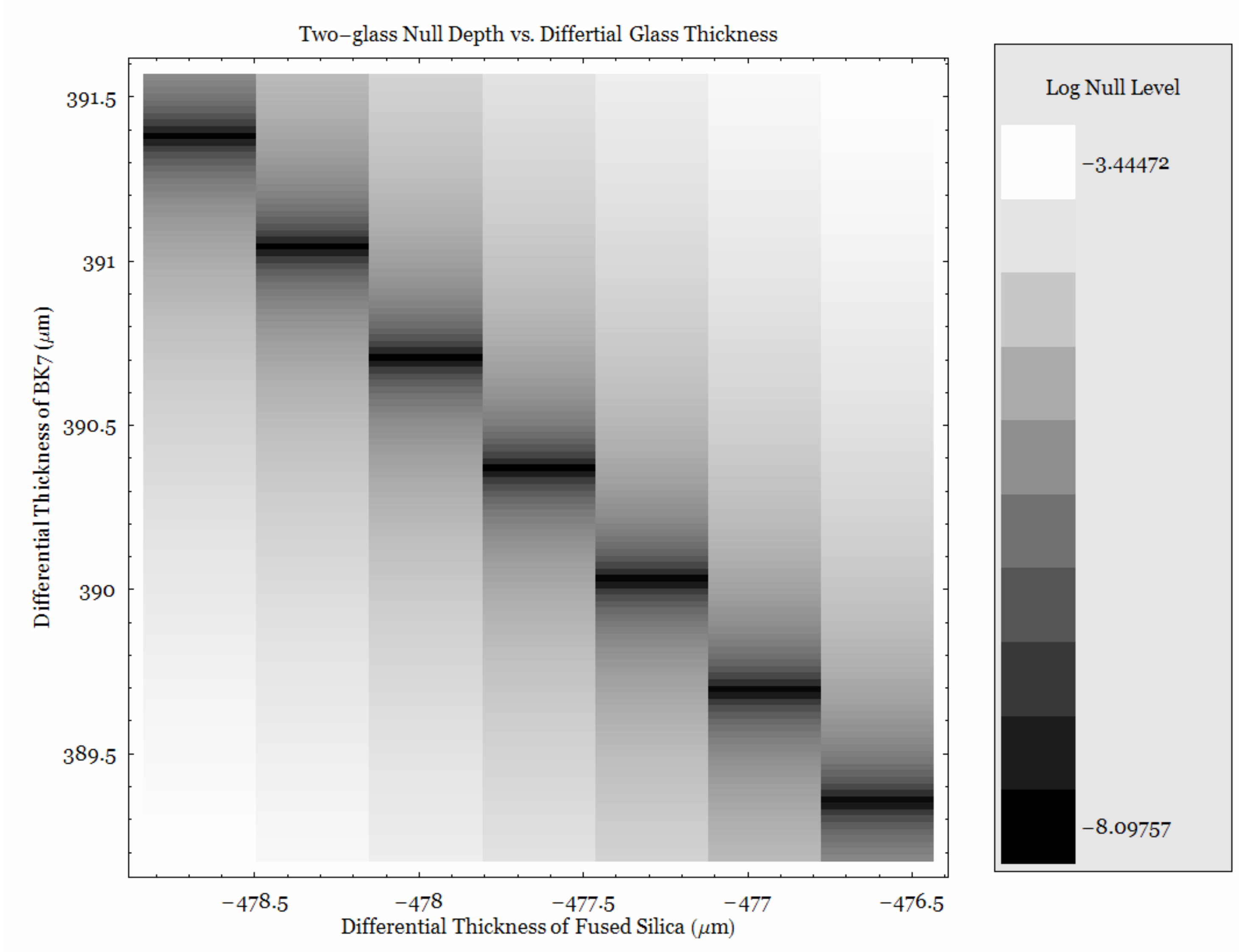
Null Space (High Resolution)



Null Space (Low Resolution)



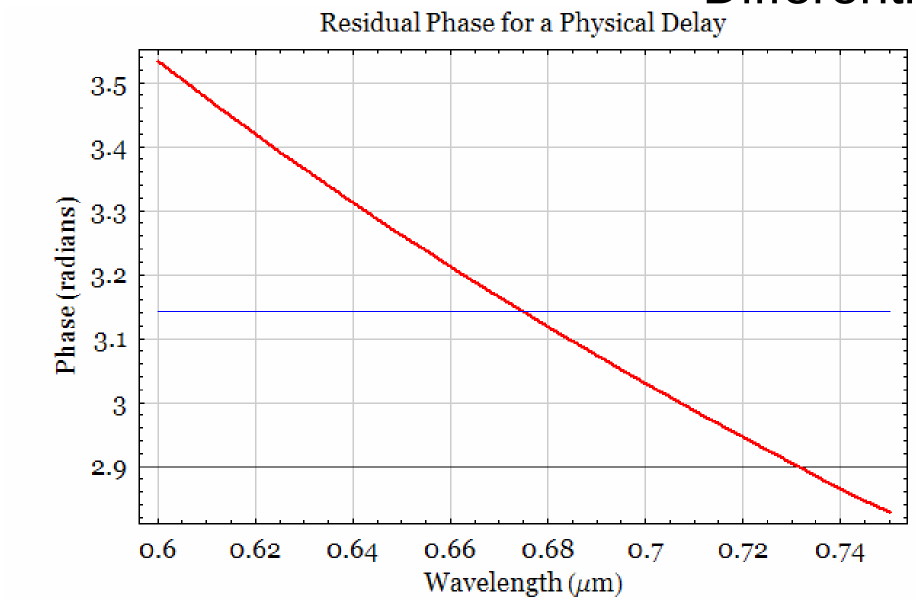
Null Space (Mixed Resolution)

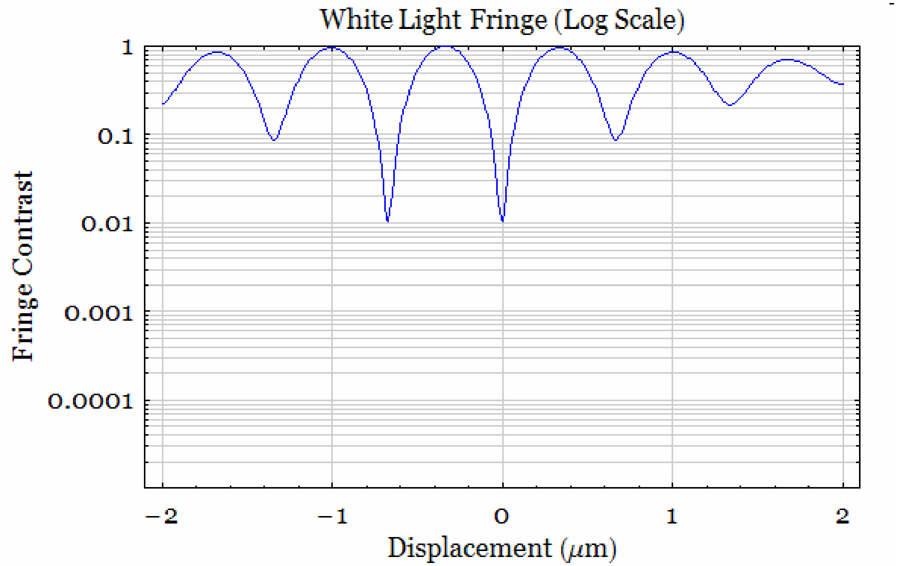


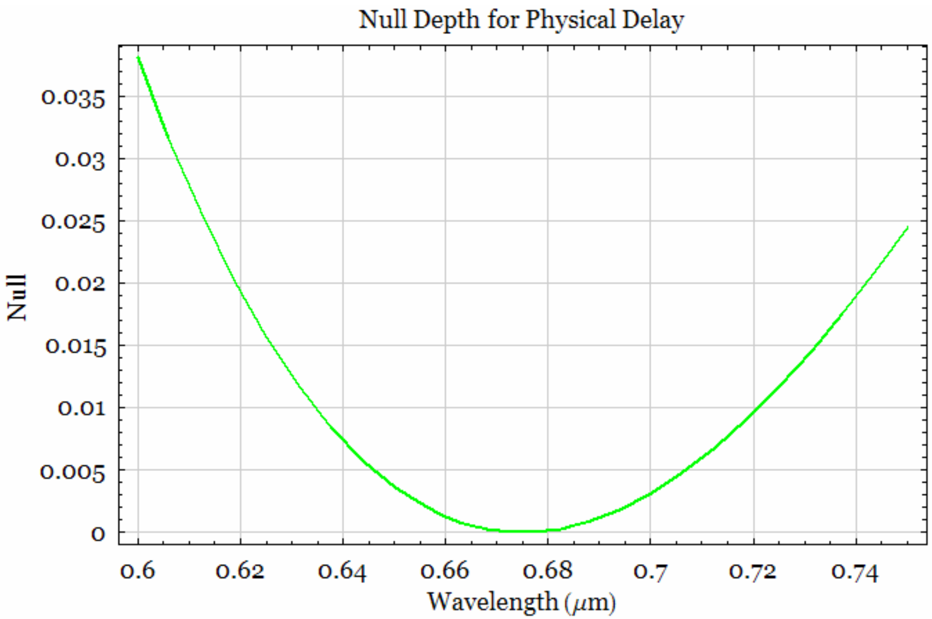
Null Space

- Histograms of Null Depth
- Vs. Temperature

Principle of Nulling with Phase Plates: Differential Air Only



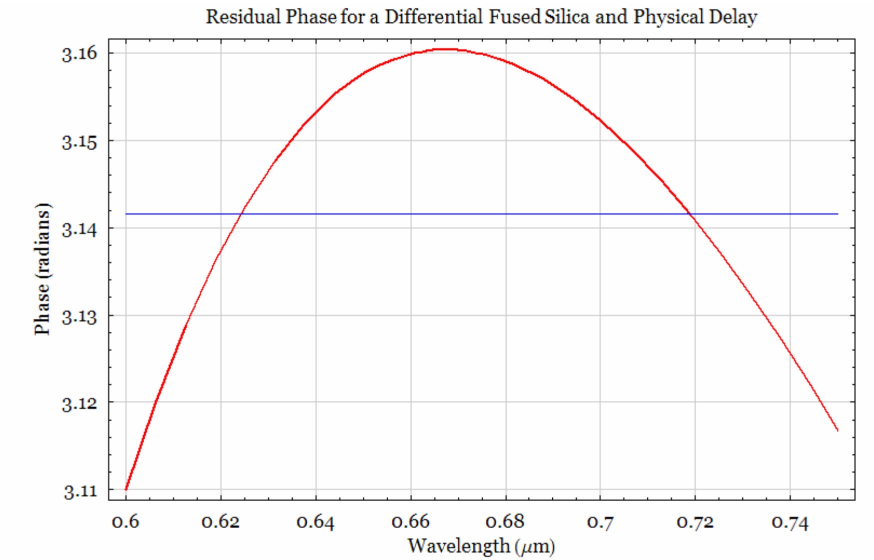


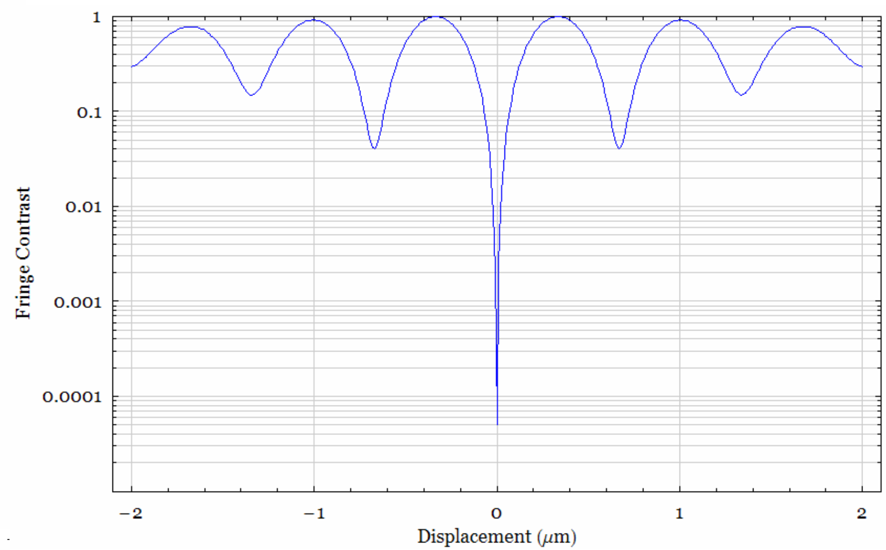


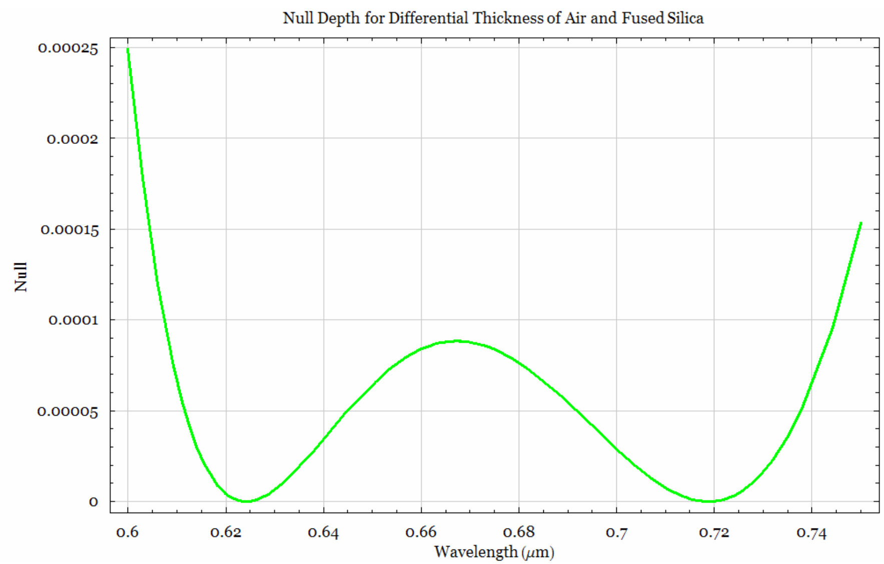
Average Null = 100:1

Lambda = 600 – 750 nm

Principle of Nulling with Phase Plates: Differential Fused Silica and Air







Average Null = 20K:1
Lambda = 600 – 750 nm

Polarization Induced Amplitude Mismatch

BK7	Nom T	Angle of Incidence	Effective Thickness	Delta T	Tp	Ts	Ip	Delta I	
1	10.16	1.816 Deg.	10.162						
2	10.16	24.26 Deg.	10.643	0.393					
Fused Silica									
2	10.16	1.816 Deg.	10.162						
2	10.16	25.725 Deg.	10.643	0.480					