Enhanced Interferometry with a Programmable Spatial Light Modulator

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by

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(POC's: Geraldine Wright and David Content)

This presentation is approved for General Public release

Presentation Summary

- Summarize the problem & innovation
- Describe the hardware and software
  - Digital Interferometry with preconditioned wavefronts
  - Hybrid Hartmann/Digital Interferometry
- Typical measurements
- Potential Applications
- Future Work

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The Problem Being Addressed

Modern optical components such as aspheres are difficult to inspect. Interferometry, the usual solution, lacks the required dynamic range. Too many fringes are produced. Adapting interferometry for null measurements currently necessitates special optical components for each inspected component.

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Innovation/Solution

- Incorporate a programmable SLM into an optical inspection instrument enabling:
  - Combined interferometry and Hartmann Sensing
  - Virtually unlimited dynamic range
  - Extended dynamic range of interferometry by preconditioning waves
  - Null testing on almost any component using off the shelf optics.
- Incorporate Instantaneous Digital Interferometry Technology

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Challenges Faced and Solved

- Incorporating the SLM into a PhaseCam
- Integrating Hartmann and Digital Interferometry
- Calibrating the SLM
  - Phase-only mode by controlling polarization
  - Corrected gamma curve, i.e. linear phase shift versus grayscale value
- Impressing the required phase function on the SLM
- Identifying and minimizing errors and noise

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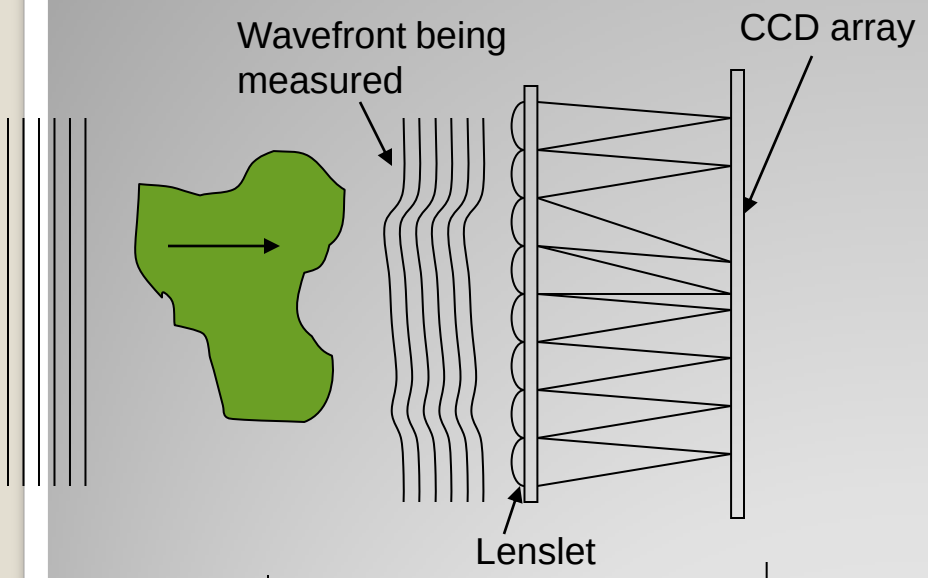
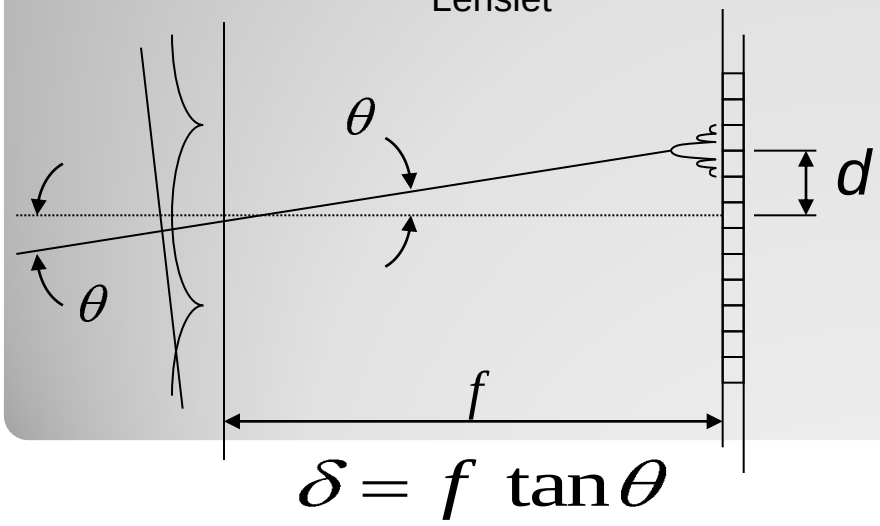
Conventional Shack-Hartmann Characteristics

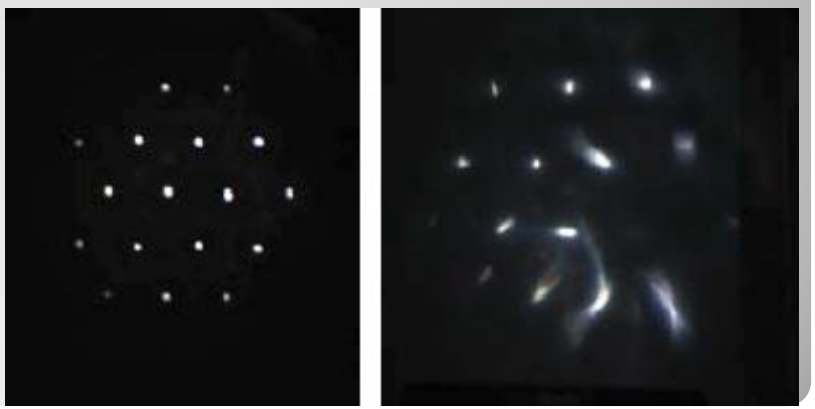




$$\delta = f \tan\theta$$

- Lenslet diameters, d, define spatial resolution over the wavefront being measured.
- δ (sensitivity) proportional to f, which should be less than d to prevent confusion

Without aberration **With aberration**



'Measuring aberration of the eye with wavefront technology '
Giuseppe Colicchi, et al
Zur Veröffentlichung eingereicht bei "Physics Education", 2006

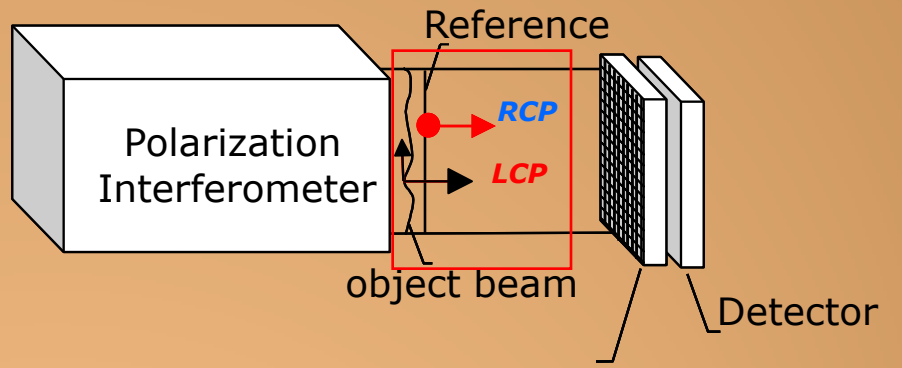
Key Components: SLM, Pixelcam*

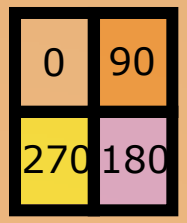
SLM for a compensator

- Programmable holographic optical element
- Produce wavefronts of any shape and can simulate freeform optical surfaces
- Holoeye SLM
  - SLM can produce a phase up to 2π at 632.8nm
  - Assign 0 to 255 grayscale values to 0 to 2π (or 1λ)
  - Can generate higher phases by wrapping phase
  - Can provide more than 150 wave tilt
  - Pixel size ~ 19 microns.
  - 19.5 x 14.6mm size (1024 x768 pixels)

Pixelated Phasecam for a detector

- Spatial phase shifting interferometer
- Single shot, insensitive to vibration



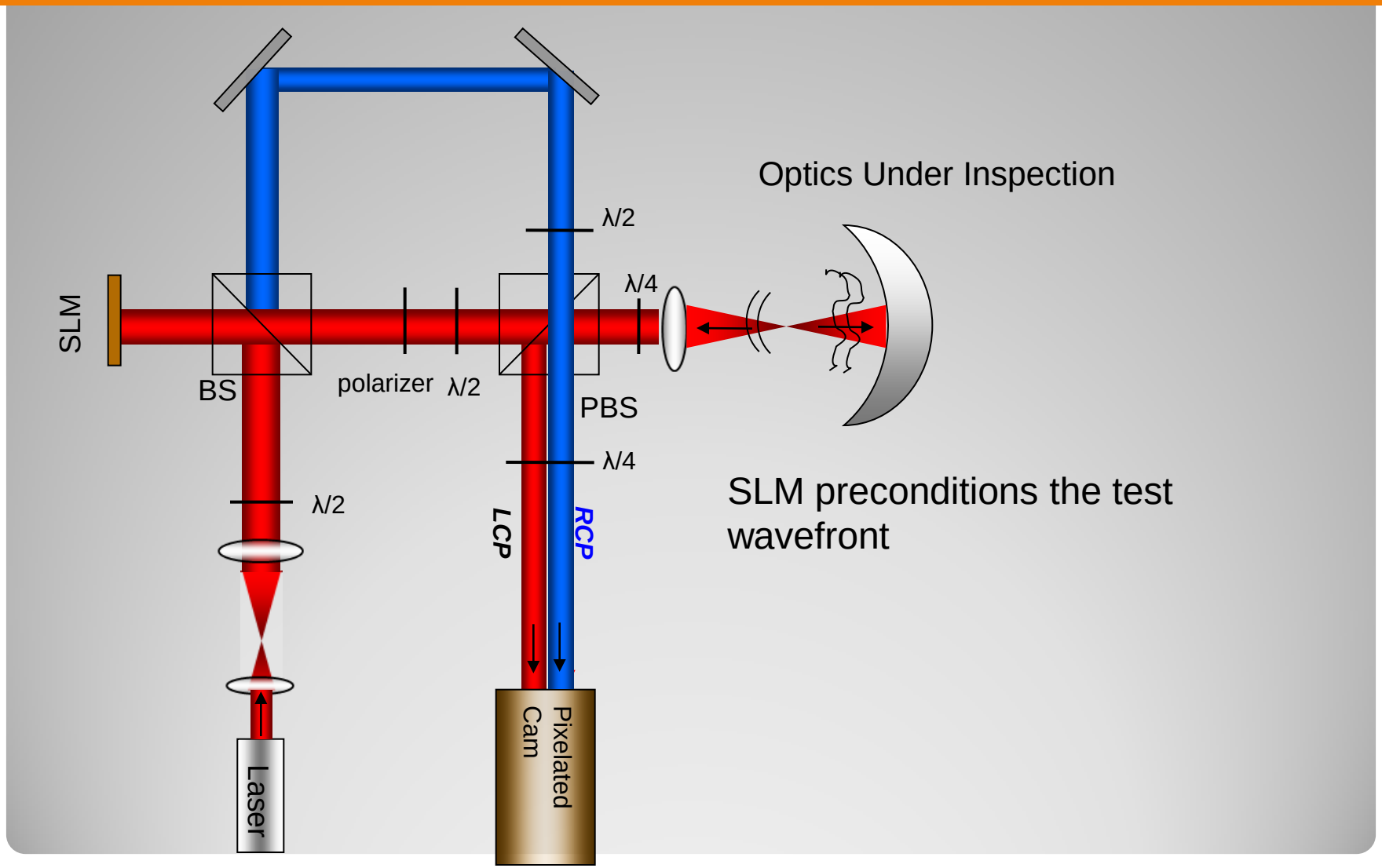


Phase information of the object, $\Delta\Phi(x,y)$ can be obtained from the 4 intensities on each unit cell.

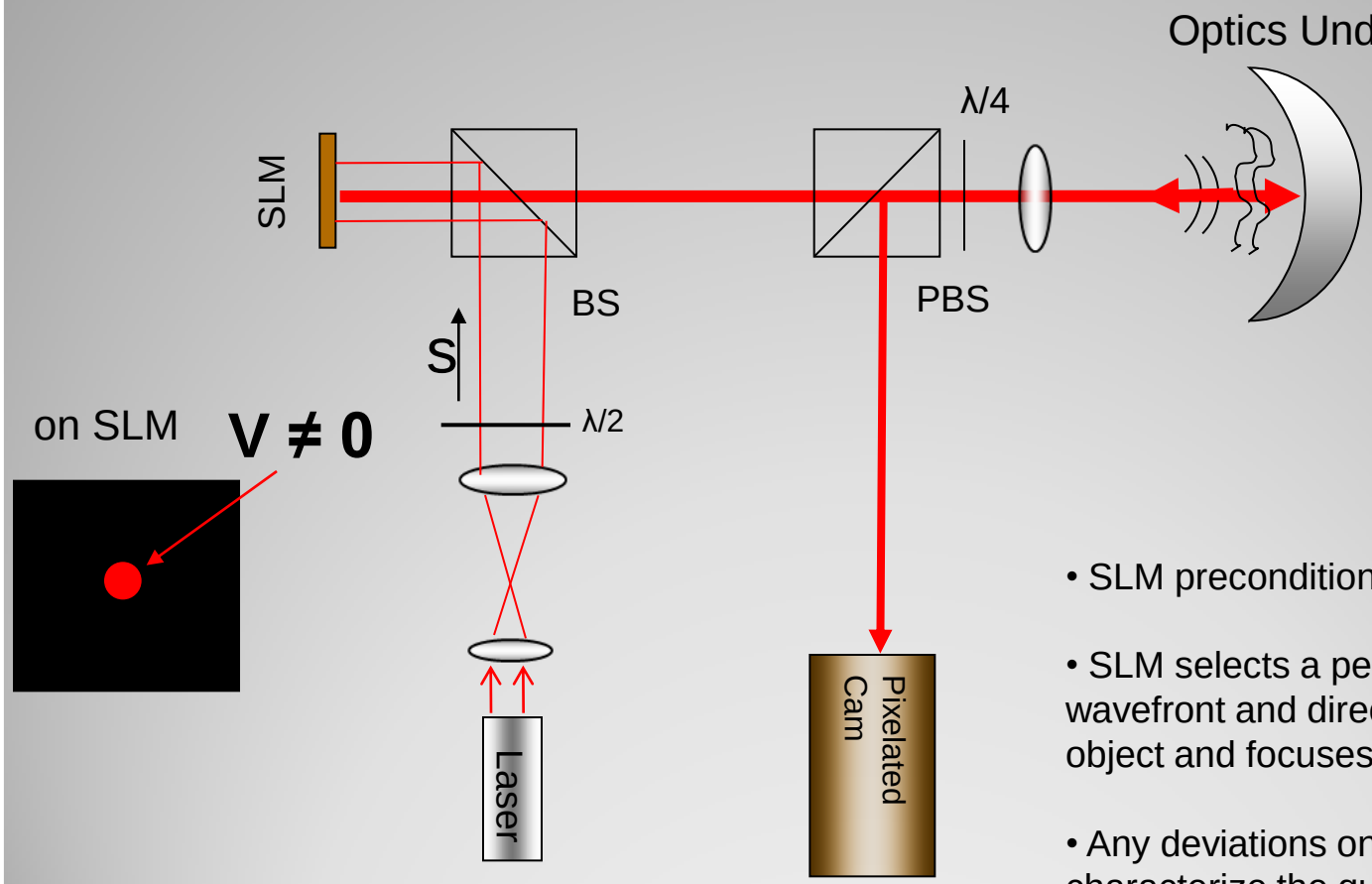
$$I(x,y)=\frac{1}{2}\left(I_r+I_s+2\sqrt{I_r I_s}\cos\left(\Delta\phi(x,y)+2\alpha_p\right)\right)$$

Produced and Trademark by 4D Technologies, Inc, Tucson, AZ* ***http://www.4dtechnology.com*

Hybrid Hartmann & Digital Interferometer



Using a SLM as a Scanning Shack-Hartmann Component



- SLM preconditions the test wavefront
- SLM selects a pencil of light from the wavefront and directs it to the test object and focuses it on the CCD
- Any deviations on CCD will characterize the quality of the test object.

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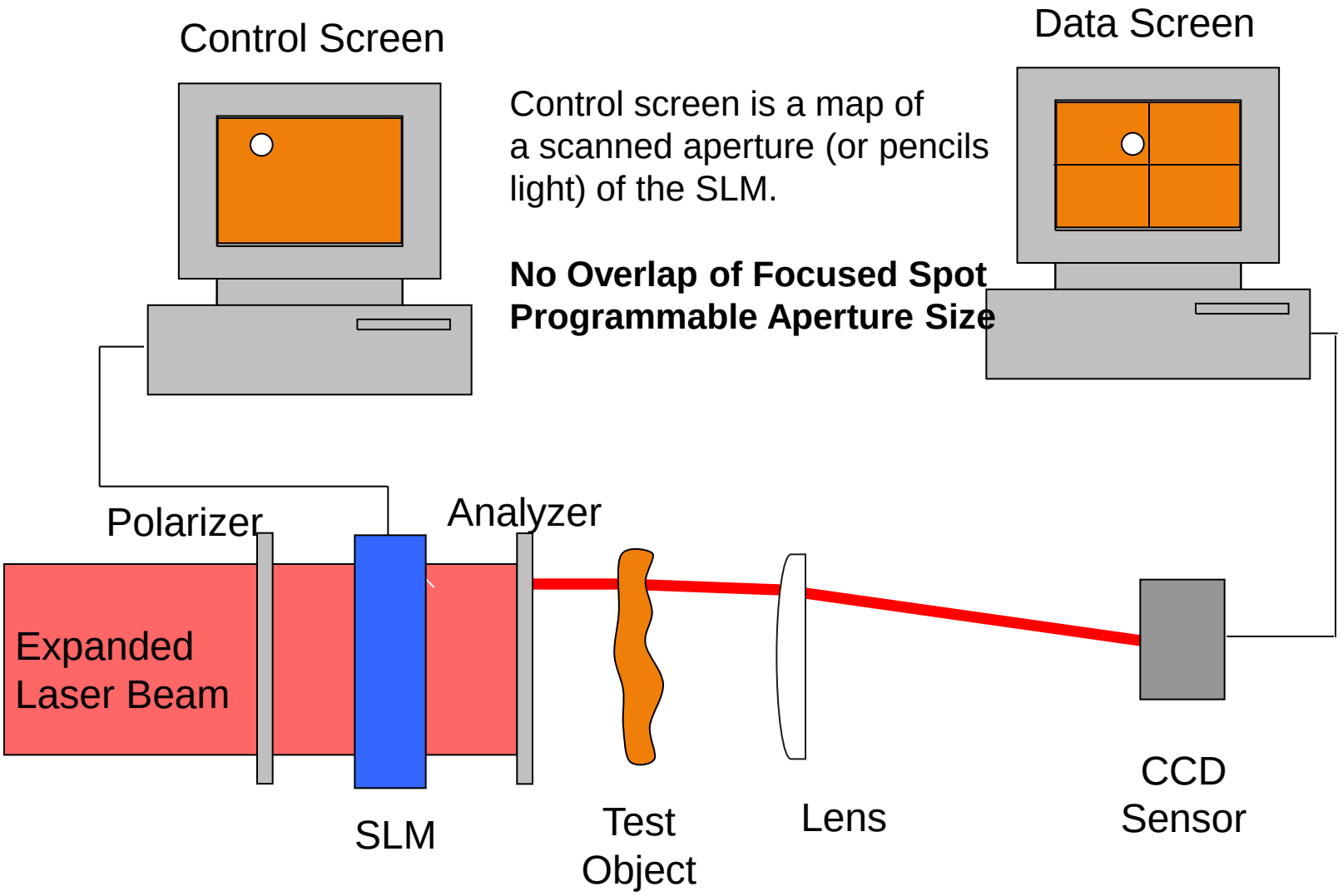
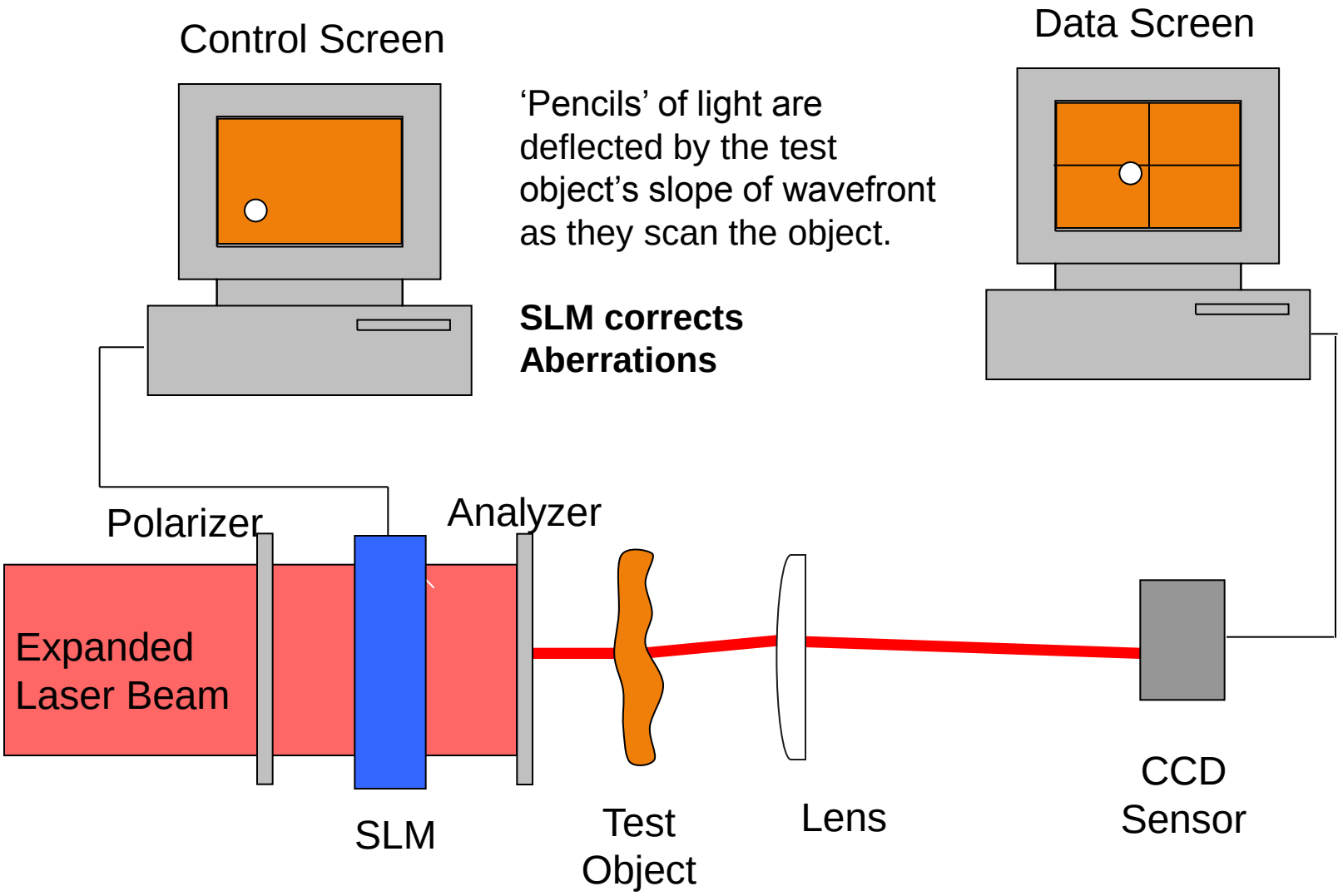
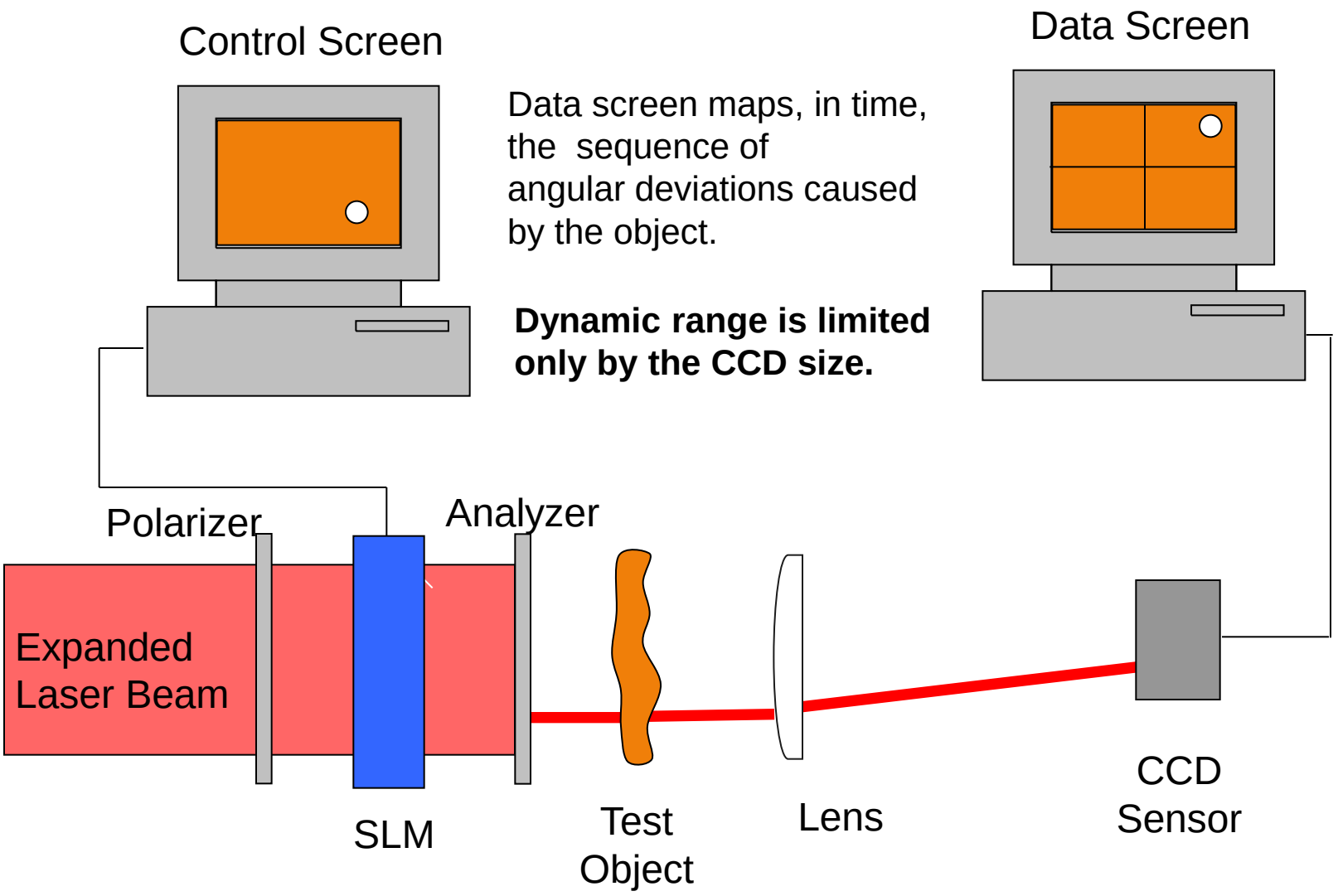
Scanning Shack-Hartmann System



Scanning Shack-Hartmann System



Scanning Shack-Hartmann System

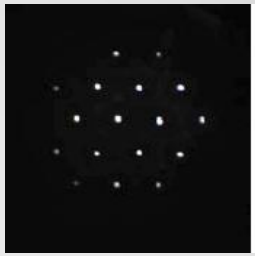


Constraints in conventional Hartmann Testing that can be obviated with this concept

- Sensitivity requires a longer focal length which can cause focused image overlap of adjacent light pencils.
  > SLM enables scanning in time, NO OVERLAP

- If the wave is aberrated, the focused spot will not be round, so its centroid is more difficult to locate, further reducing accuracy
  > SLM enables preconditioning/aberration correction

- Spatial resolution is limited to the diameter of the lenses in the array.
  > Limited to fractional pixel size of SLM



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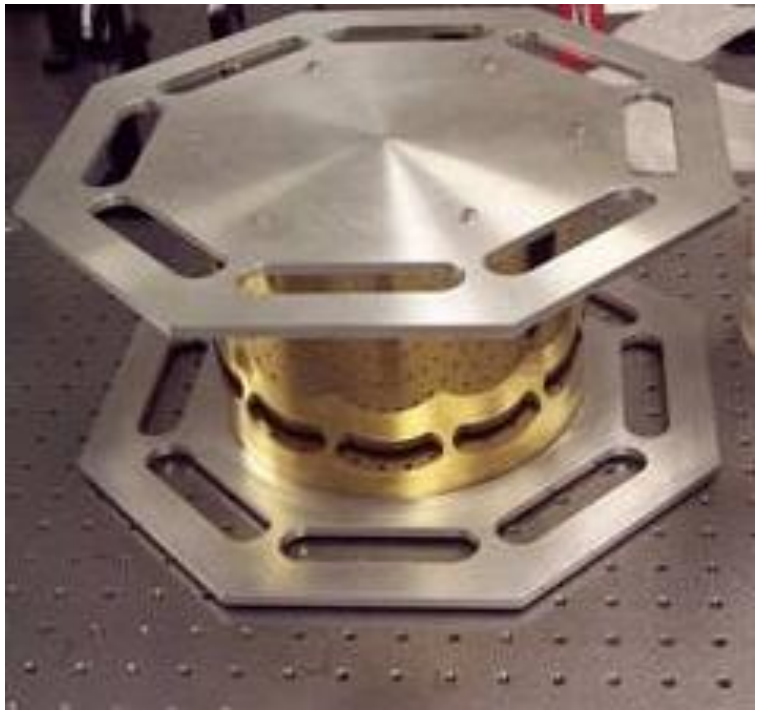
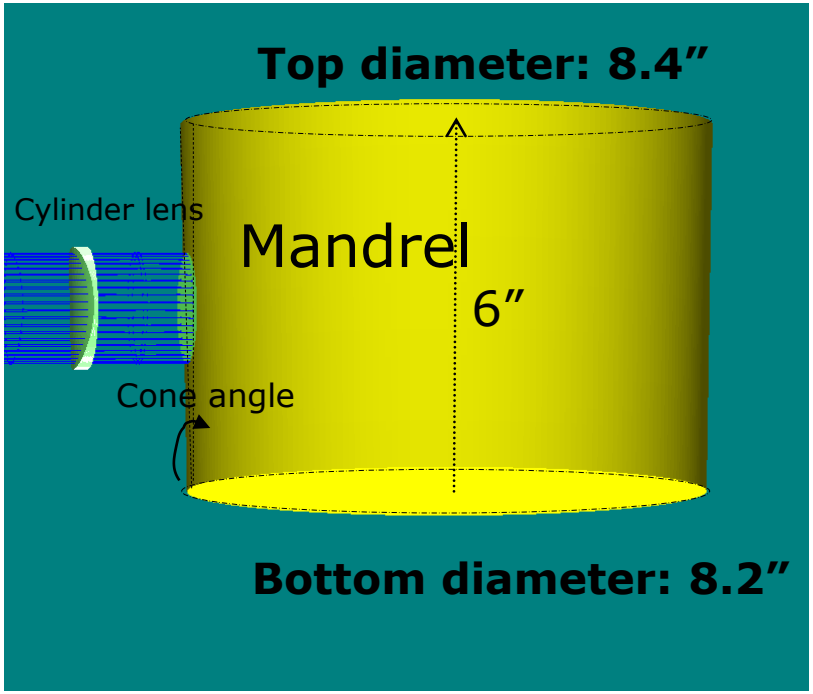
Mandrel Used for Demonstration

Photo of the Mandrel



Geometry of the Mandrel



• Mandrel provided by NASA GSFC, 6-inches tall, top and bottom diameters are different, cone shape.

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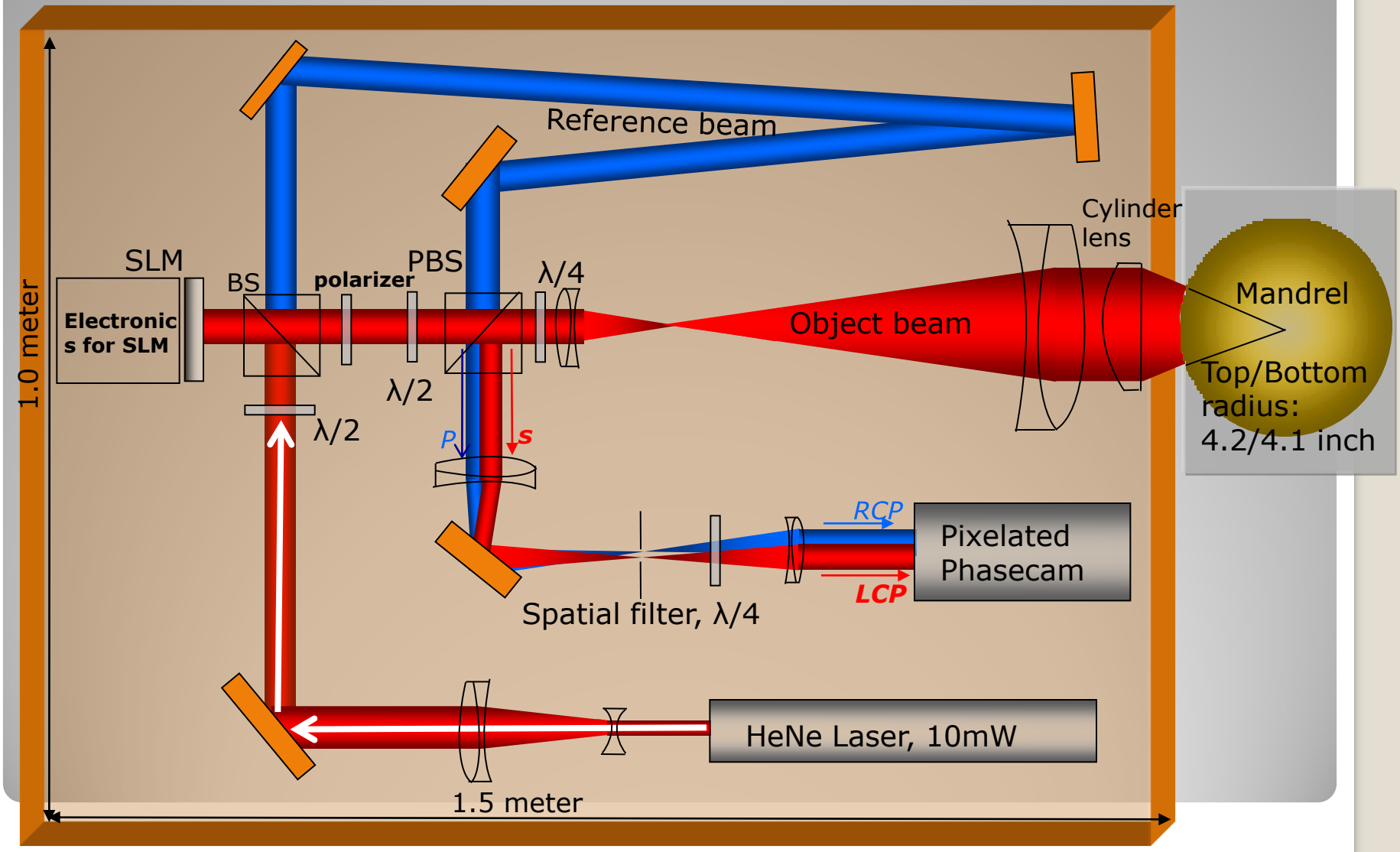
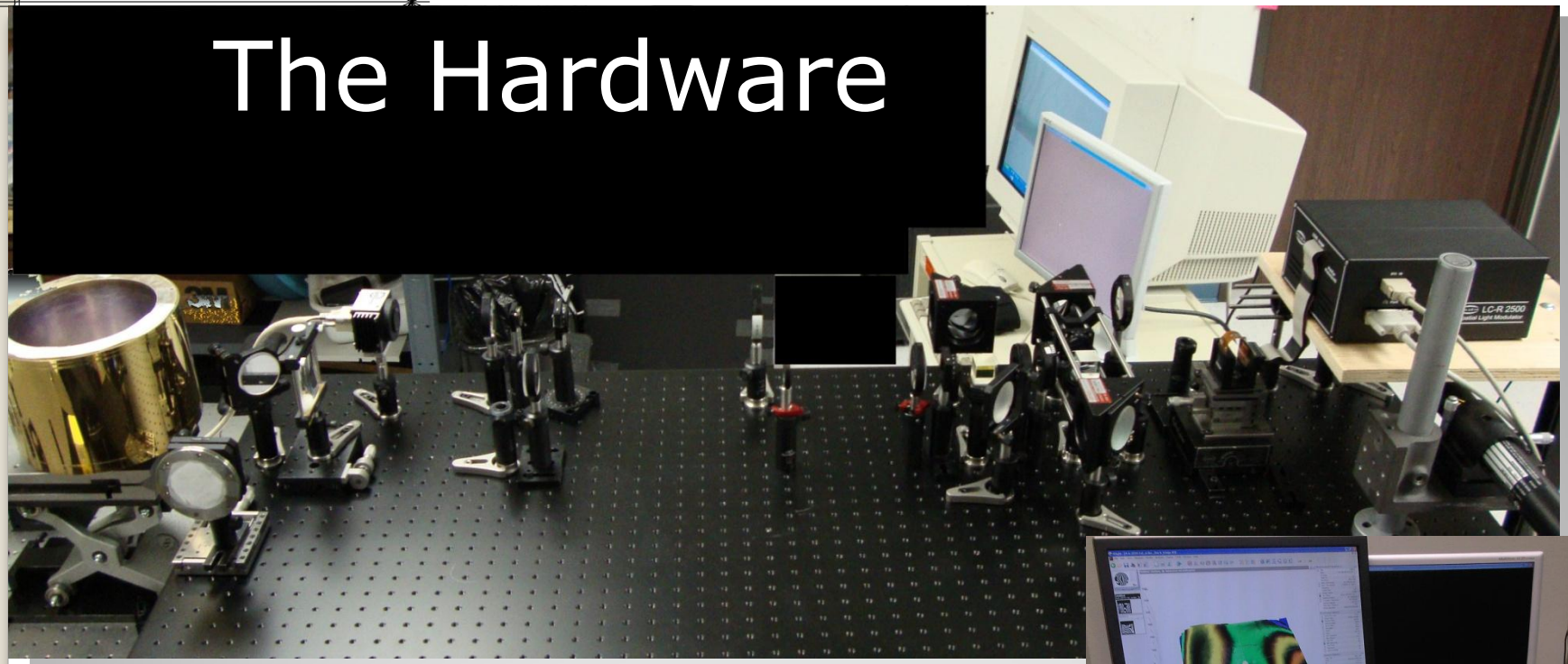
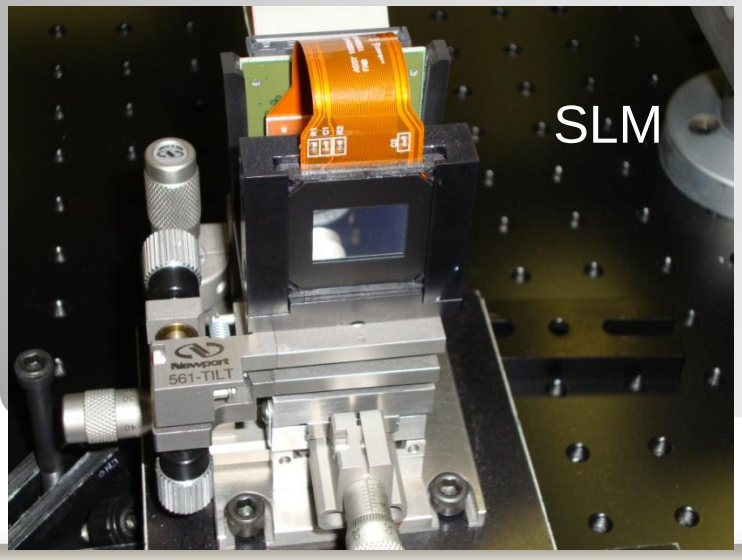
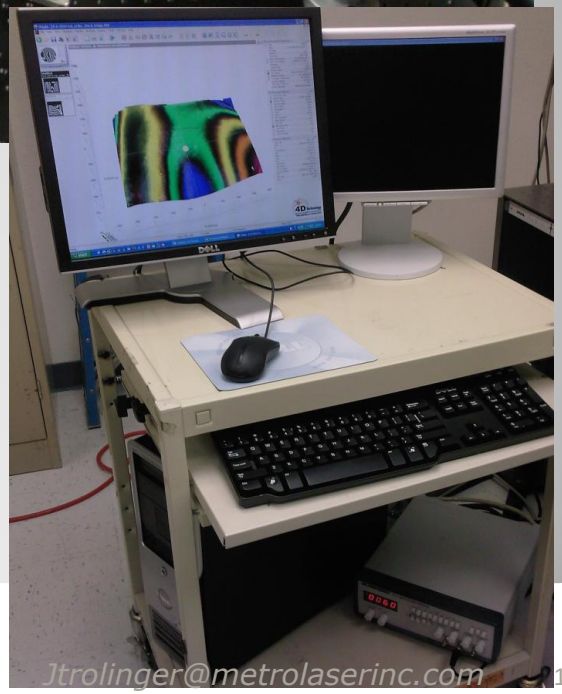
System Design (Top view)



The Hardware

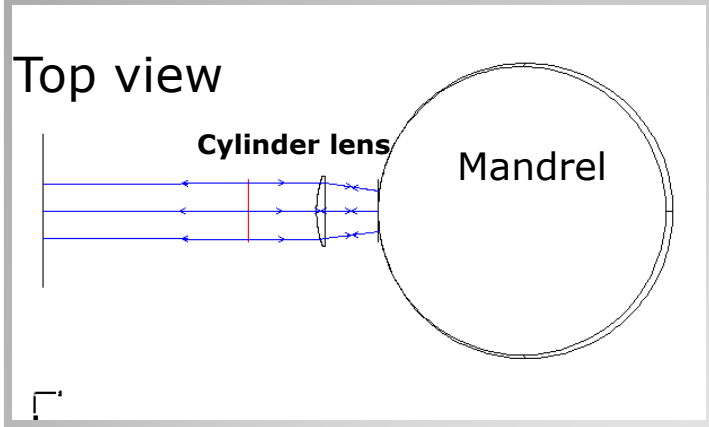


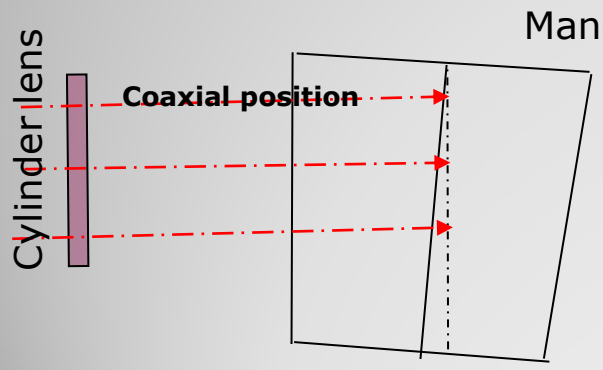




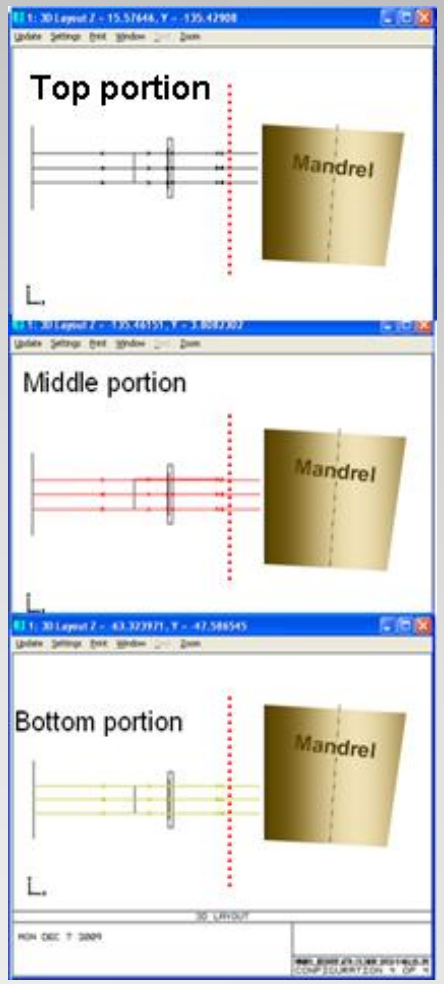
Simulation Results

Beam size at cylinder lens: ~1.8inch
150mm fl cylinder lens

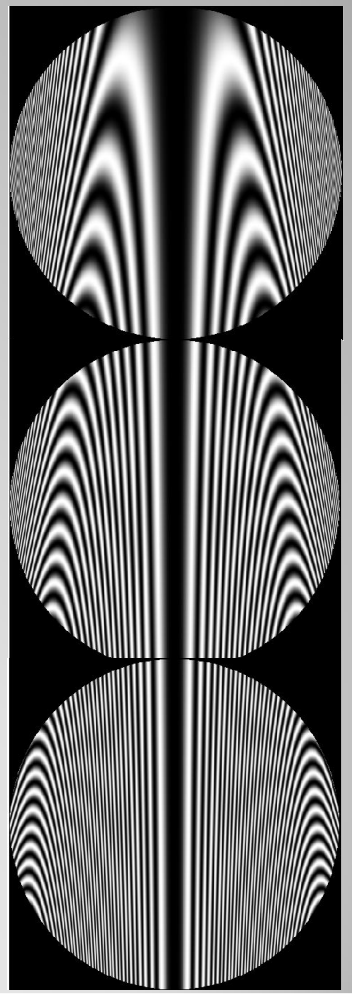




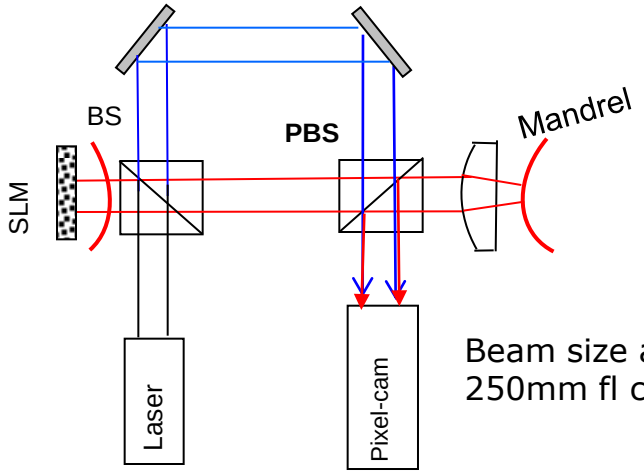
Side View



Interferogram



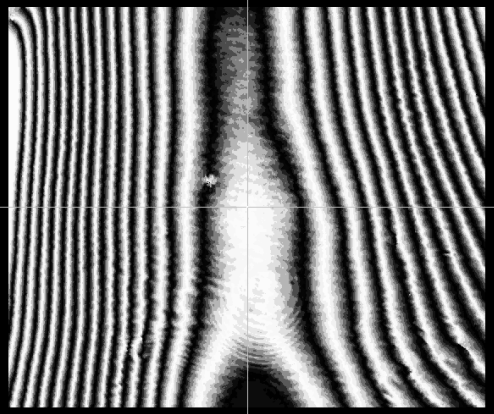
Reducing the number of Fringes from a mandrel



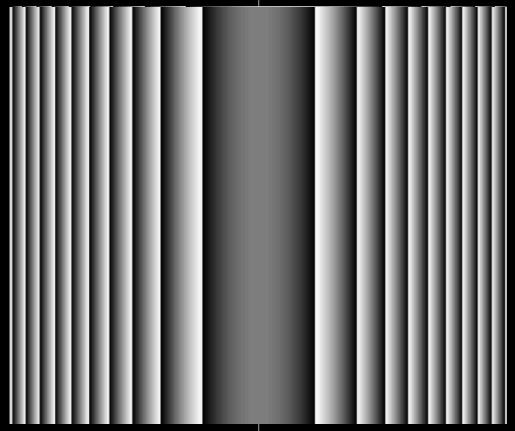
Beam size at cylinder lens: ~1.5inch.
250mm fl cylinder lens used

(Various waveplates and telescopes not shown)

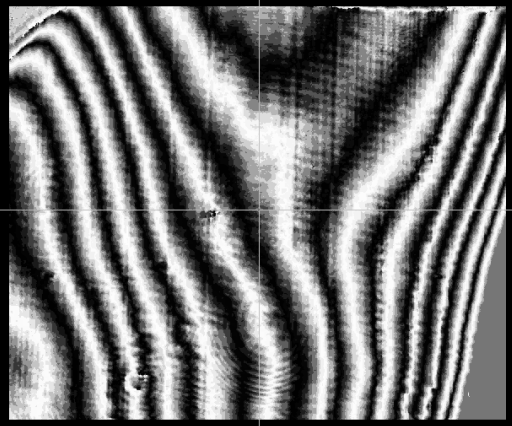
Measured Interferogram



Applied Phase on the SLM

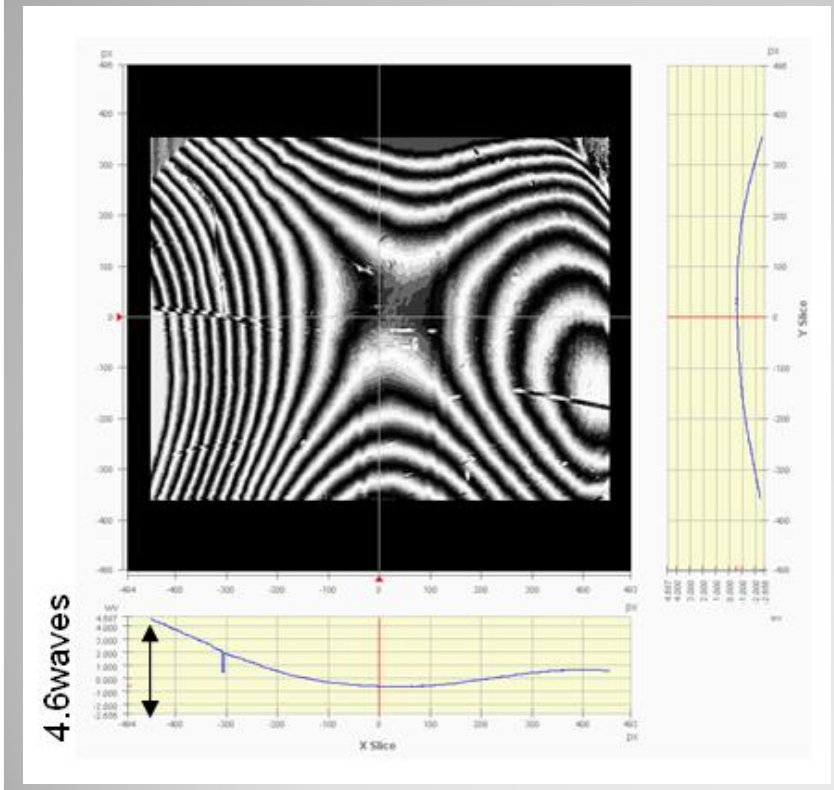


Residual Interferogram

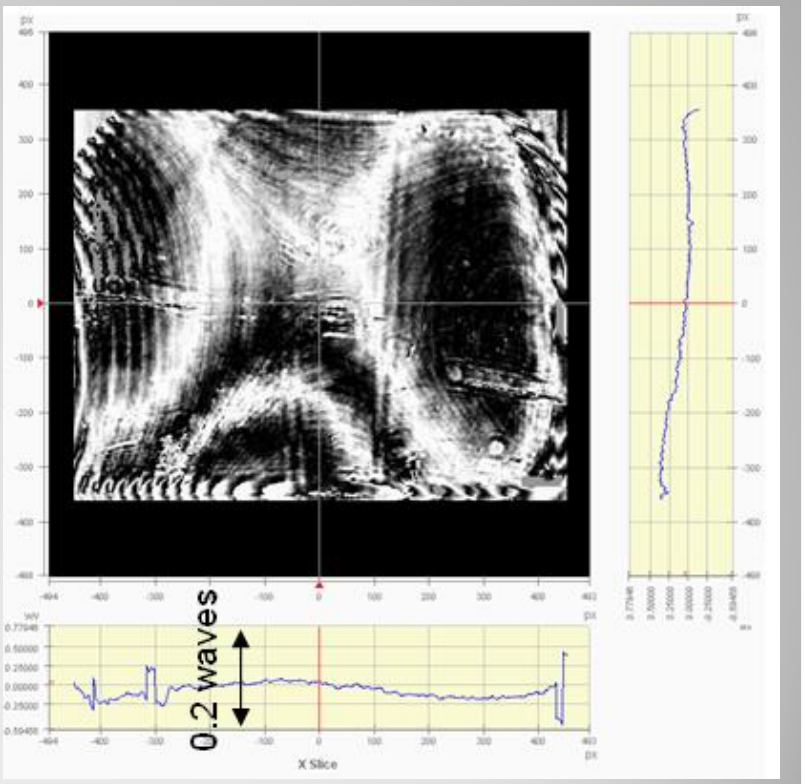


Compensation of one of Mandrel's wavefronts for a one inch beam

Before Compensation

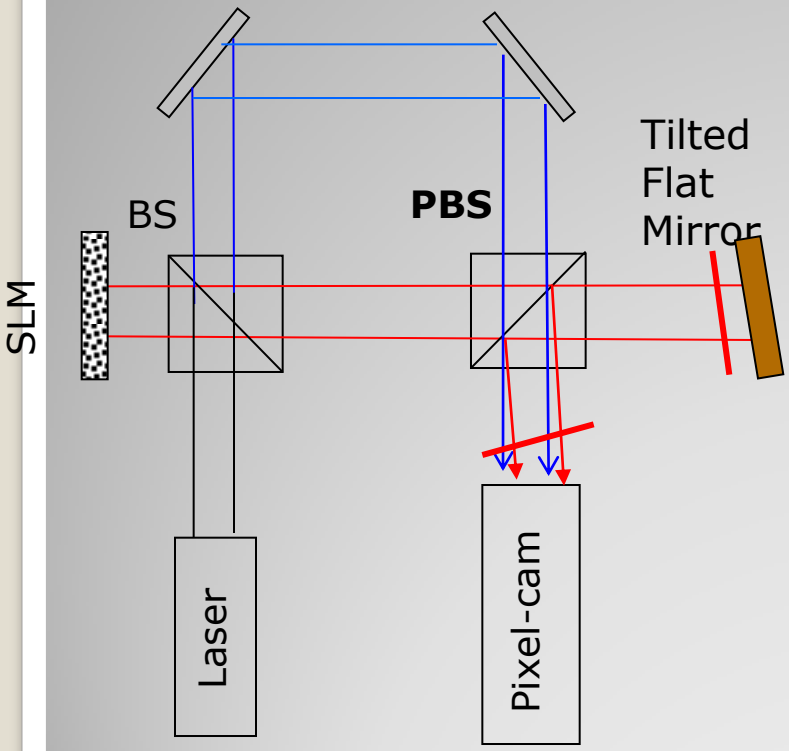


After Compensation



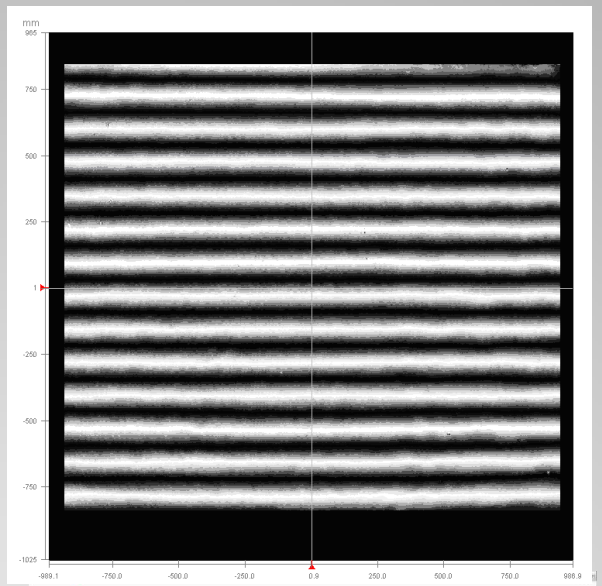
Resolution & Signal to Noise

-Tilt by the flat mirror, ~7 waves



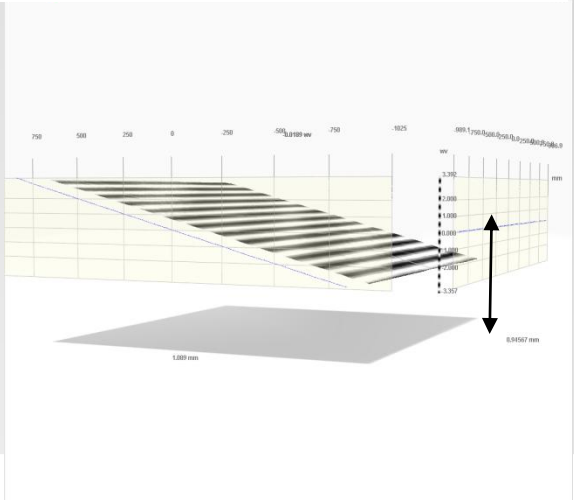
(Various waveplates and telescopes not shown)

Tilt introduced by flat mirror



Interferogram

~ 14 fringes

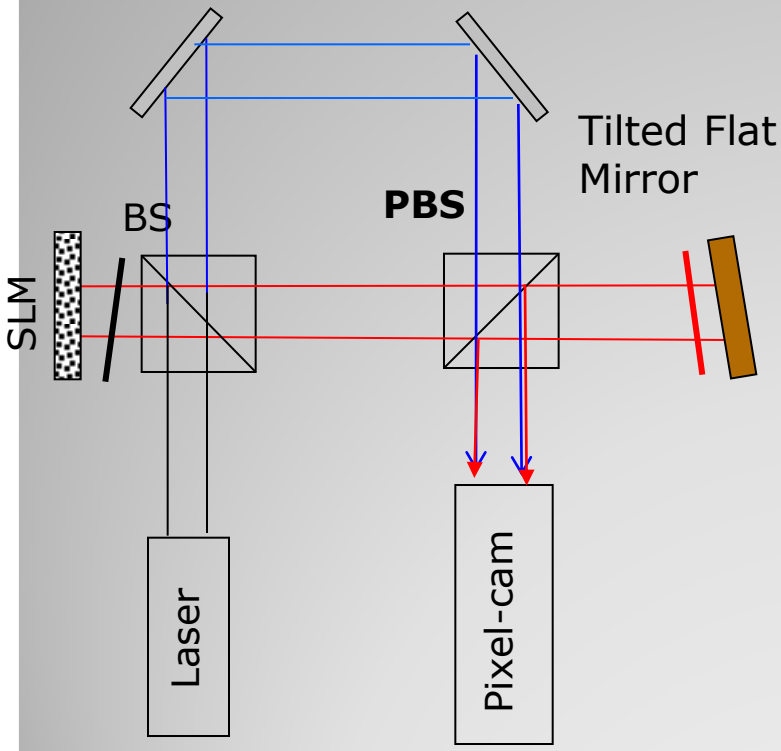


3D view

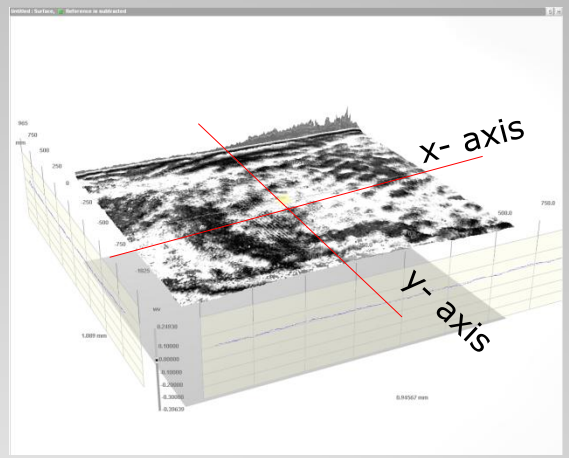
PV. ± 3.4 λ

Resolution and Signal to Noise (Cont.)

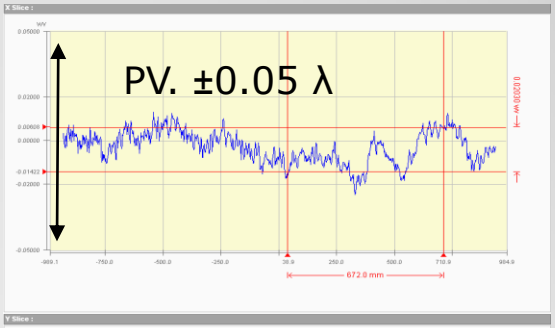
- Residual wavefronts, less than 0.05 λ



(Various waveplates and telescopes not shown)



Interferogram
(3D view)

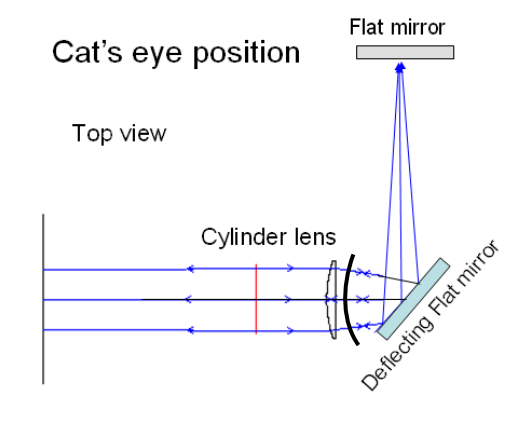


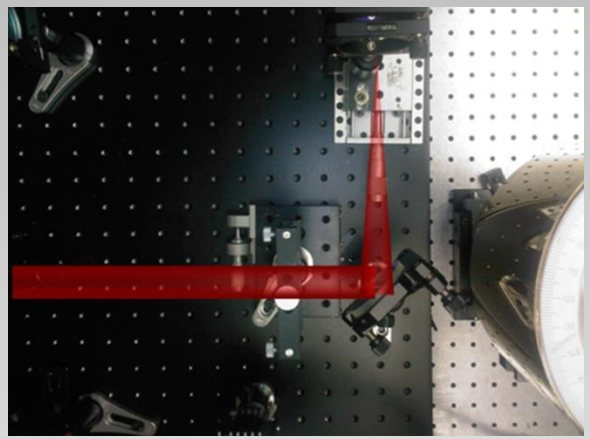
x-profile

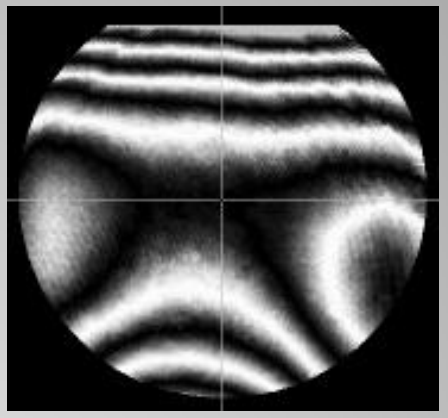
y-profile

SLM can compensate tilted wavefronts with an accuracy of 1/20th wave, or better

Determining System Aberrations with a Cat's Eye

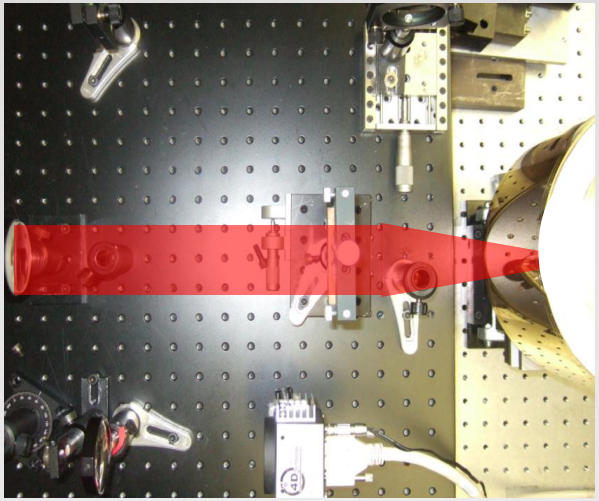


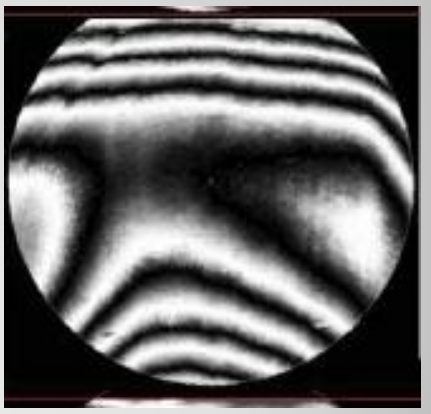




Due to SLM, cylinder lens, optical alignments, etc

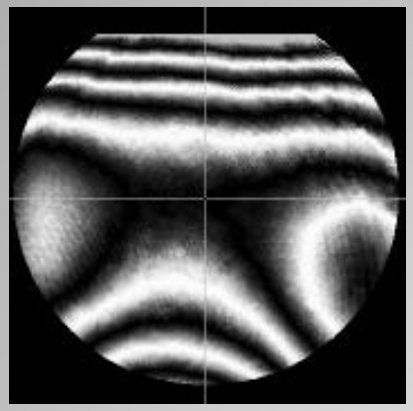
Coaxial position



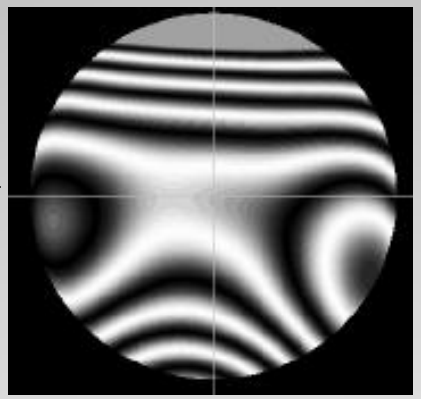


Cat's eye wavefronts by ZEMAX based on Experimental results

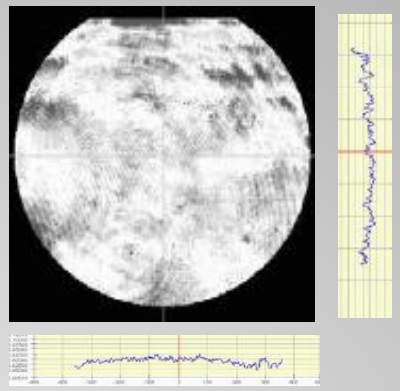
Experimental measurement



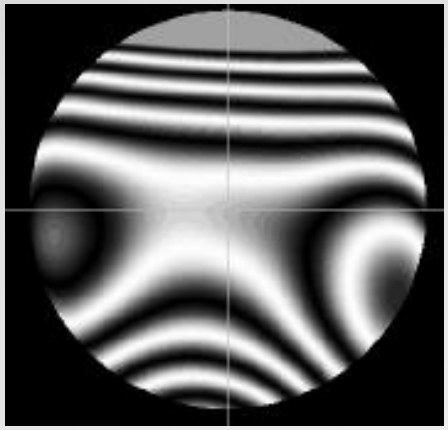
Simulated Fringes



Leftover < 0.1λ

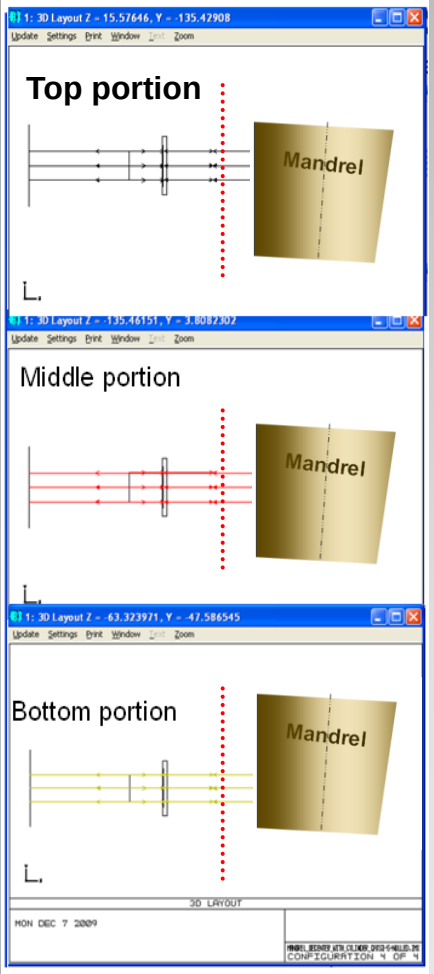


Fitted Zernike Polynomials upto 36 terms, found and put into Zemax



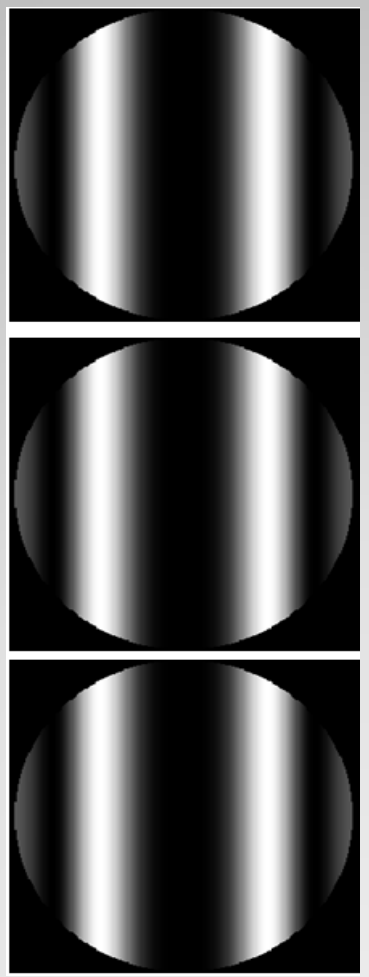
Simulated Cats' eye wavefronts by ZEMAX

Side View

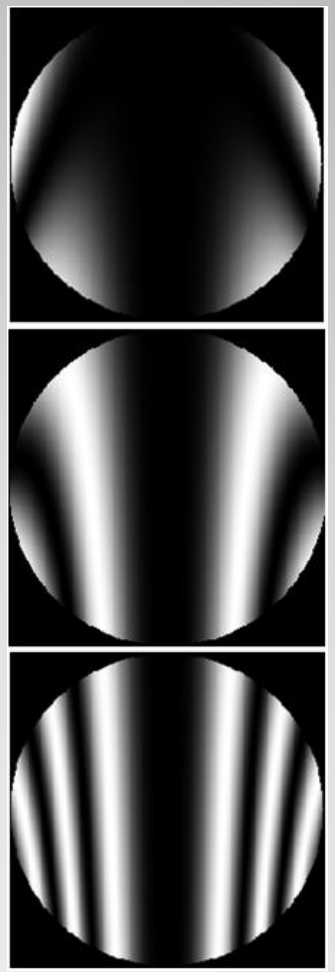


Beam : ~27mm

Simulated, No System Aberrations

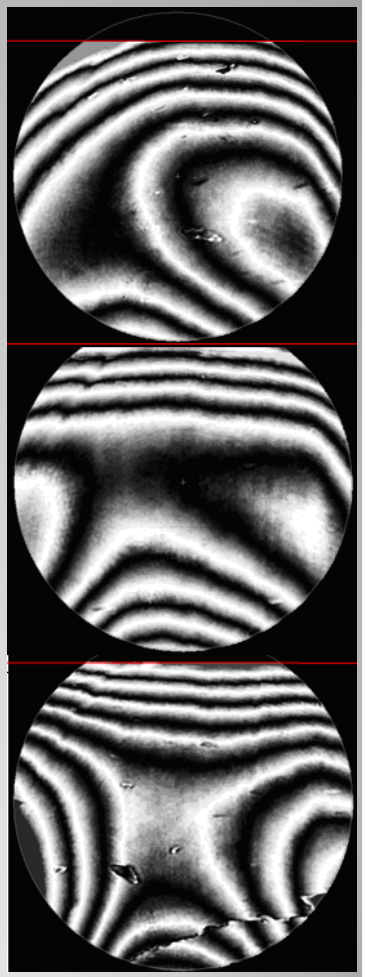


Wavefronts at cat's eye position at each height



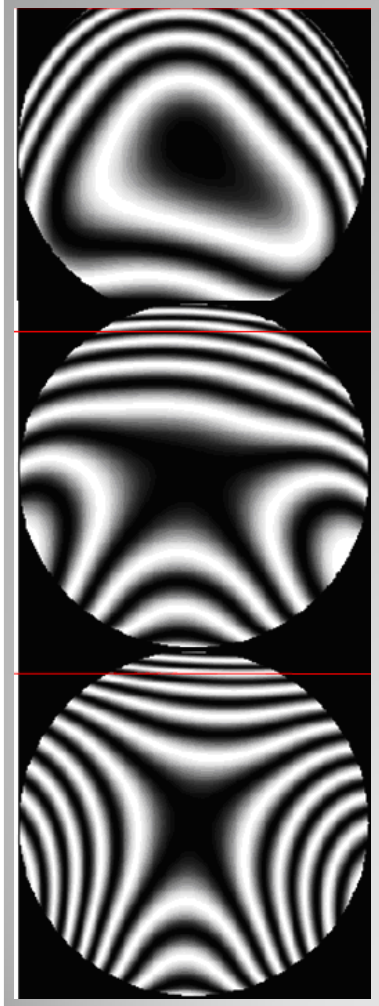
Wavefronts at coaxial position at each height

Measured

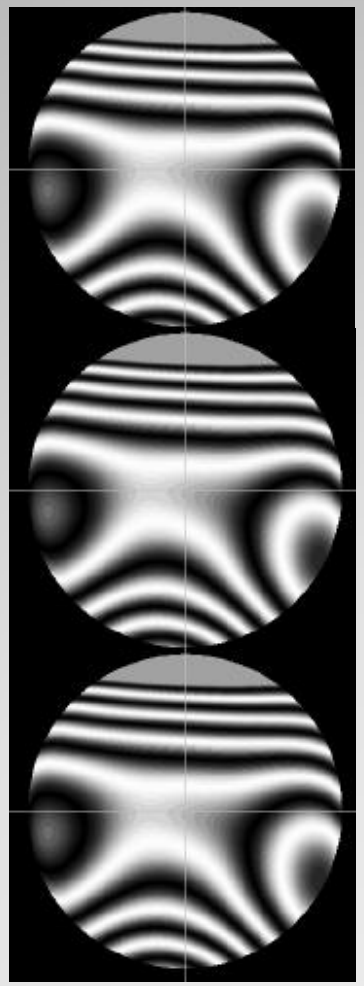


Wavefronts at coaxial position at each height

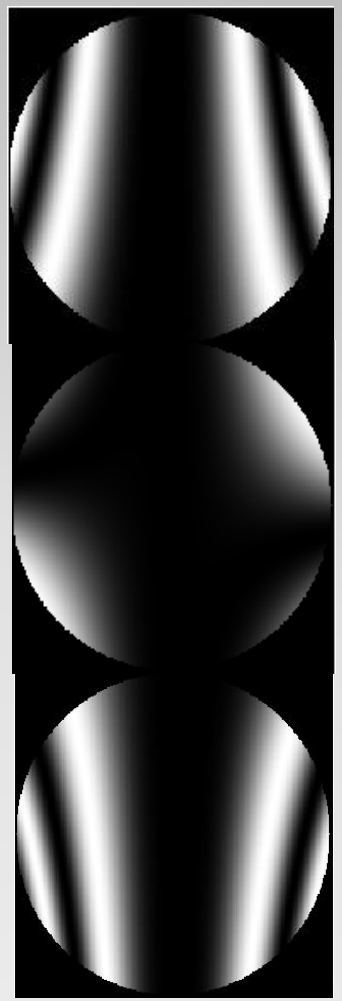
Net fringe due to a Mandrel



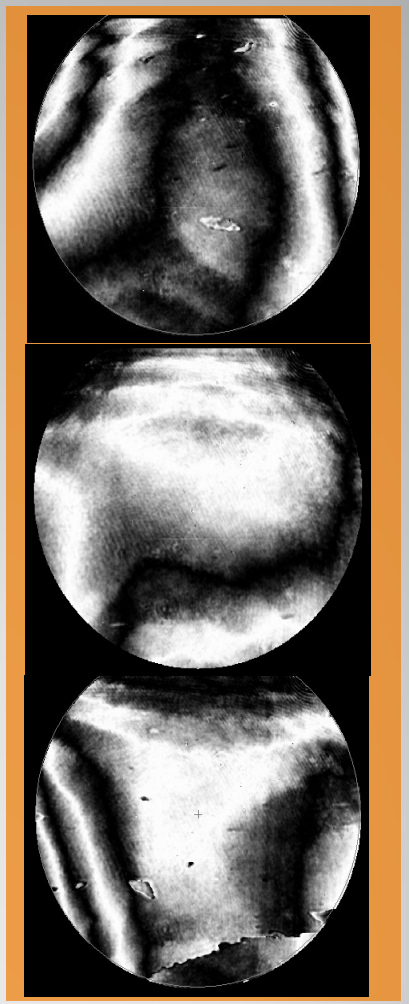
Coaxial position



Cat's eye position



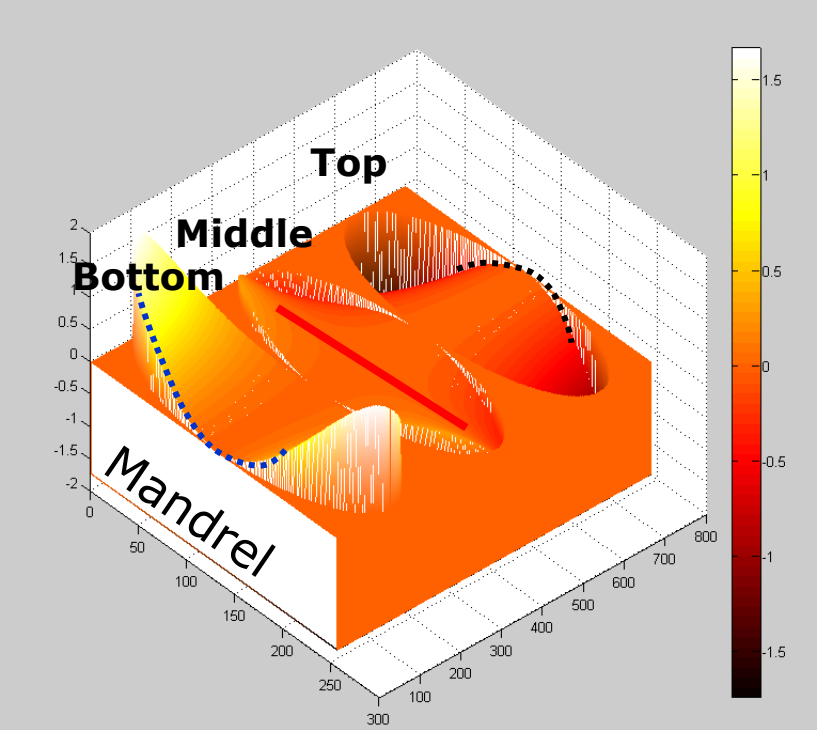
Simulated Net Fringes



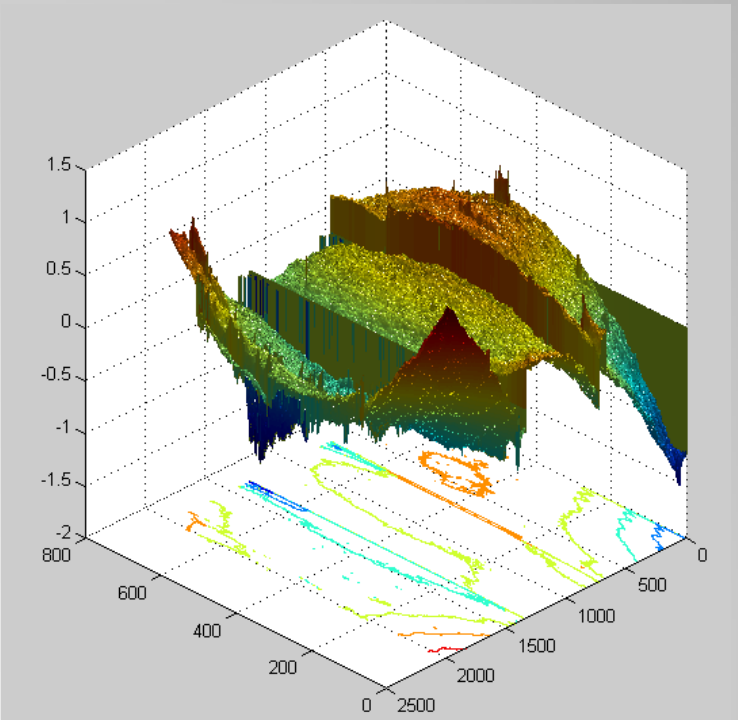
Experimental Net Fringes

Wavefronts from the Mandrel, II

Simulated Wavefronts of the Mandrel



Experimental Wavefronts



Unique Features & Applications

- Very wide dynamic range
- Applicable to aspheres and non axi-symmetric optics, i.e. freeform optics
- Enables null point testing
- Enables removing system aberrations

Summary and Conclusions

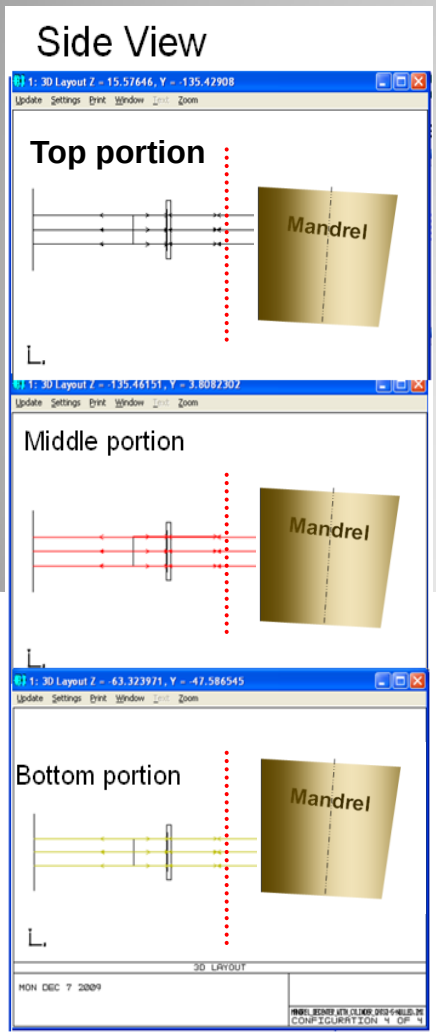
- Demonstrated wide dynamic range digital interferometry/Hartmann for advanced optical components using an SLM to:
  - provide wavefront preconditioning.
  - Hartmann & Interferometry in the same instrument
  - Scanning Hartmann
  - extended dynamic range.
  - Null point testing.
- Hartmann provides information needed to program SLM for wavefront preconditioning
- SLM Calibration procedure to produce Gamma curve.
- Procedure to subtract system abberations.
- Accuracy of $\lambda/20$ with SLM in system.
- Concept extends dynamic range by more than 150λ

Future Work

- Software Development
  - Transforming Hartmann data into wavefront Preconditioning data.
  - Automating Calibration
  - Interferogram stitching
  - System automation
- Hardware improvements
  - Calibration to push system accuracy
  - Incorporating improved SLM’s
  - System packaging

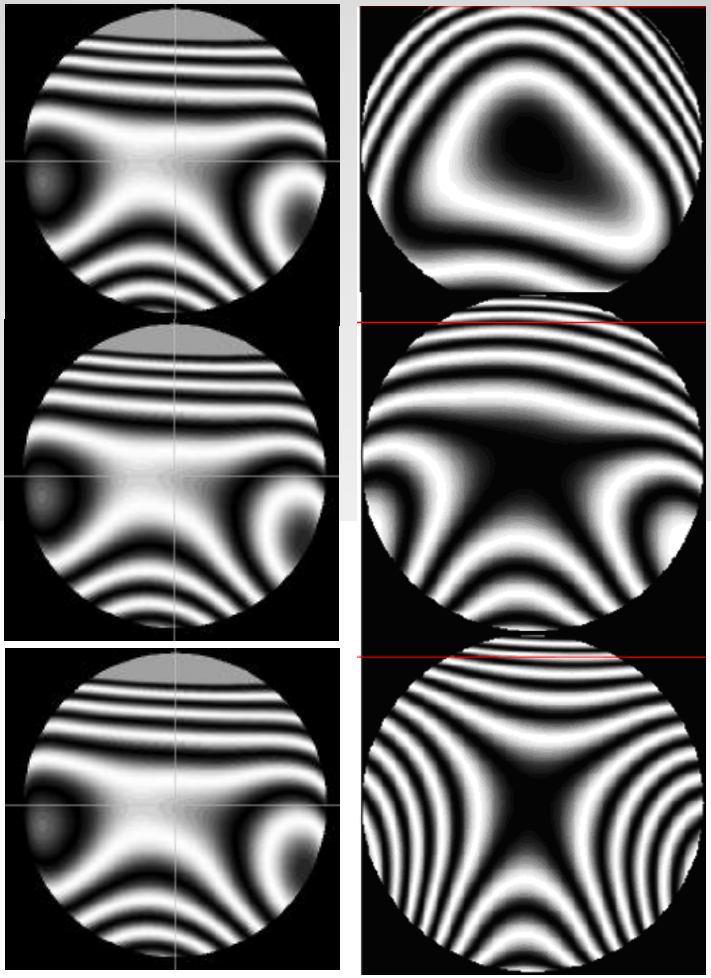
Back up Slides

Including System Aberrations



Beam : ~27mm

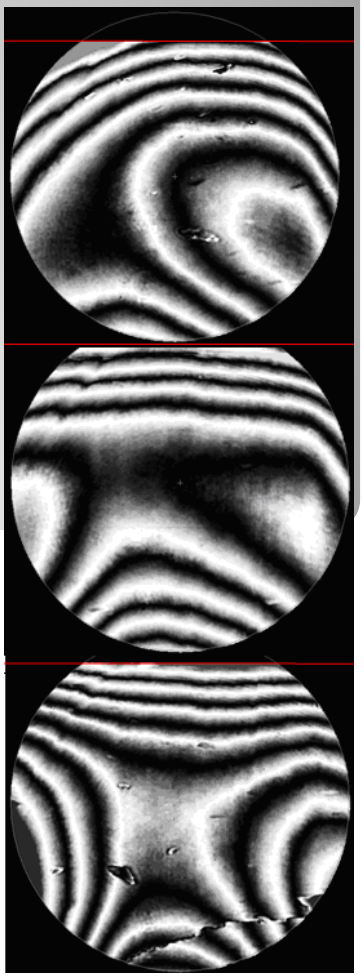
Simulated



cat's eye position

coaxial position

Measured

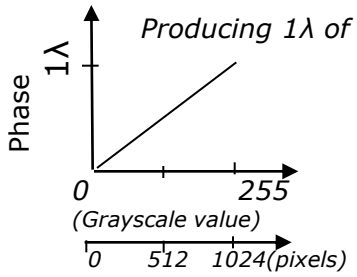


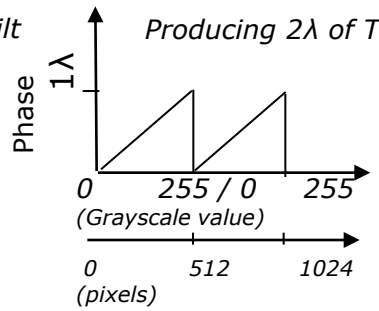
coaxial position

Key Components: SLM, Pixelcam*

SLM for a compensator

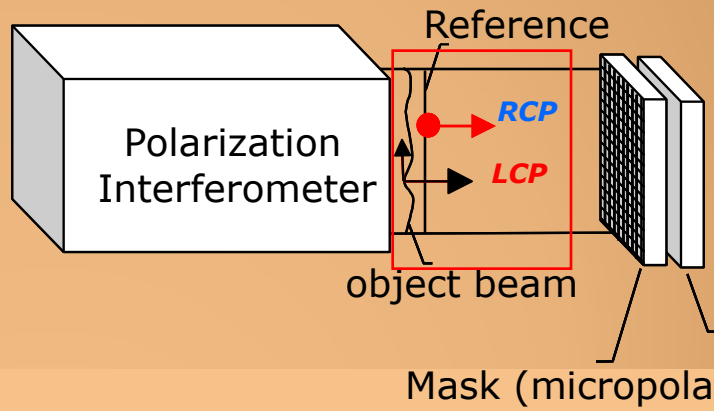
- Programmable holographic optical element
- Produce wavefronts of any shape and can simulate freeform optical surfaces
- Holoeye SLM
  - SLM can produce a phase up to 2π at 632.8nm
  - Assign 0 to 255 grayscale values to 0 to 2π (or 1λ)
  - Can generate higher phases by wrapping phase
  - Can provide more than 150 wave tilt
  - Pixel size ~ 19 microns.
  - 19.5 x 14.6mm size (1024 x768 pixels)

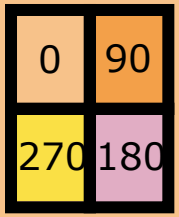




Pixelated Phasecam for a detector

- Spatial phase shifting interferometer
- Single shot, insensitive to vibration





Phase information of the object, $\Delta\Phi(x,y)$ can be obtained from the 4 intensities on each unit cell.

$$I(x,y)=\frac{1}{2}\left(I_r+I_s+2\sqrt{I_r I_s}\cos\left(\Delta\phi(x,y)+2\alpha_p\right)\right)$$

Produced and Trademark by 4D Technologies, Inc, Tucson, AZ* ***http://www.4dtechnology.com*

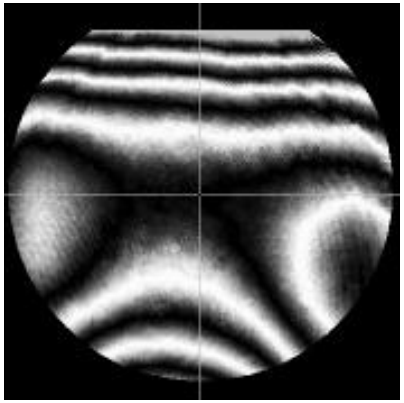
Small Business Innovation Research

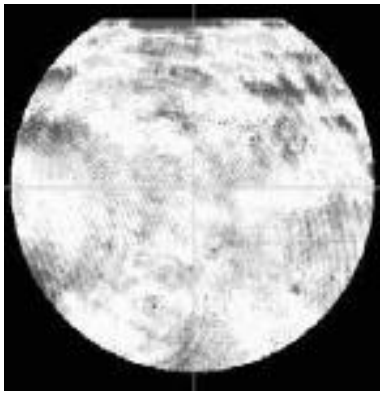
Enhanced Interferometry with a Programmable Spatial Light Modulator

MetroLaser Incorporated
Irvine, CA

INNOVATION

A unique optical inspection system incorporates a dynamic holographic optical element that combines and extends both Hartmann and digital interferometry with preconditioned wavefronts. The resulting system exhibits a wide dynamic range and will be especially useful for inspecting aspherical and free form optics





Before Correction *After Correction*
Wavefront Preconditioning

ACCOMPLISHMENTS

❖Demonstrated wide dynamic range optical inspection system
•Wavefront preconditioning via spatial light modulator.
•Hartmann & Interferometry in the same instrument
•Scanning Hartmann
•Extended dynamic range >150λ.
•Null point testing.

❖Hartmann provides information for programming SLM/HOE
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COMMERCIALIZATION

- Basic concept patent application has been submitted
- Marketing to manufacturers of free form and aspherical optics
- Currently beta testing systems in service tests
- A wide range of customers have indicated interest
- Alliances made with two specific manufacturers
- This technology can provide significant savings of time and money over competitors
- This technology can enable inspections not provided by any competitors

APPLICATIONS/FUTURE WORK

- Government and Commercial Applications
  - X-ray telescope mirrors and mandrels
  - Free form Optics
  - Aspherical Optics
  - SiC telescope Mirrors
  - Ogive windows
- Future Work
  - Additional Software for System Operation and Automation
  - System Packaging
  - Noise floor and resolution improvement

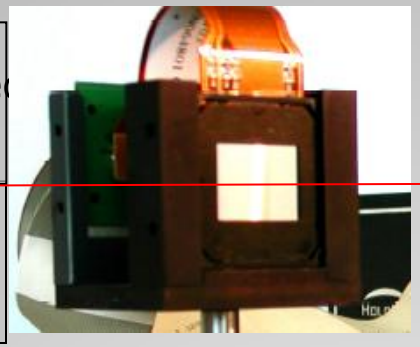
SBIR Phase II contract no. NNX08CA25C Date: May, 2010
NON-PROPRIETARY DATA for Public Release
Contacts:MetroLaser, Inc. 9495530688
jtrolinger@metrolaserinc.com

SLM Calibration

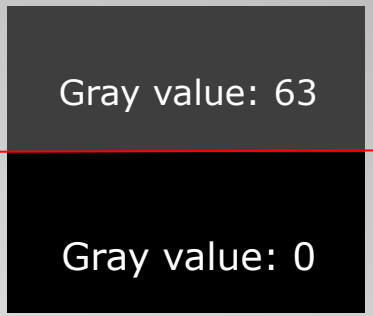
SLM

Gray scale value is varied on upper half of SLM

Gray scale value is held constant at 0 on lower half of SLM



Applied gray values on the SLM

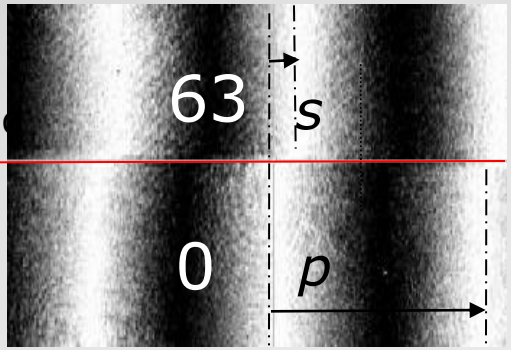


...

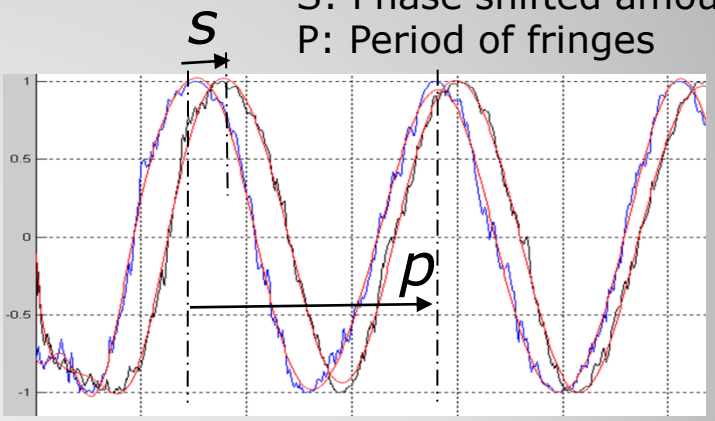
Applied gray values on the SLM

Phase shift vs. gray scale value is measured interferometrically

Interferogram Result

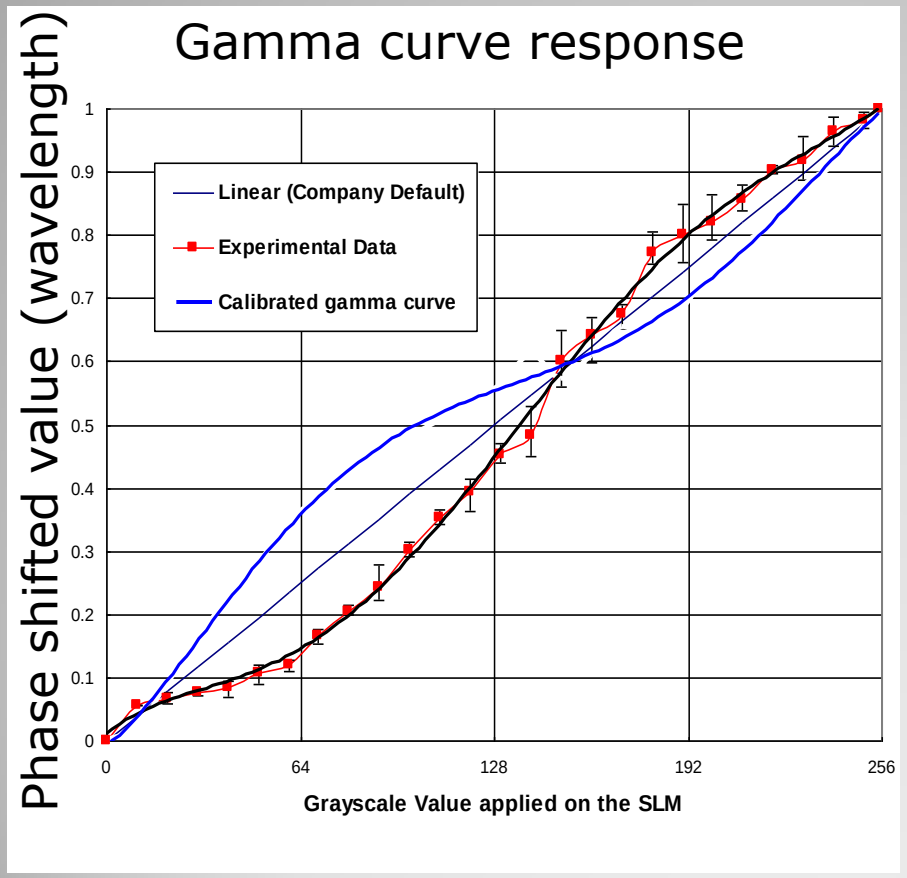


S: Phase shifted amount
P: Period of fringes



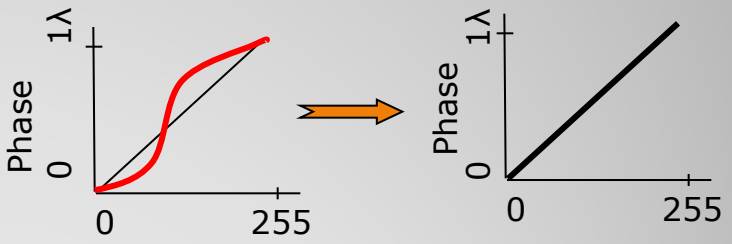
- Relative phase shift recorded to achieve an accuracy of data
- Gray value was varied from 0 to 255 on the top half, while it was held constant (0) on the bottom half
- Phase shifted vs applied gray value on the SLM produces gamma curve

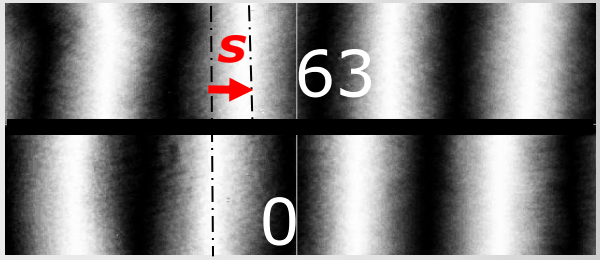
Corrected Gamma Curve



The calibrated gamma curve (blue color), is used to linearize the phase vs. gray scale response (red curve)

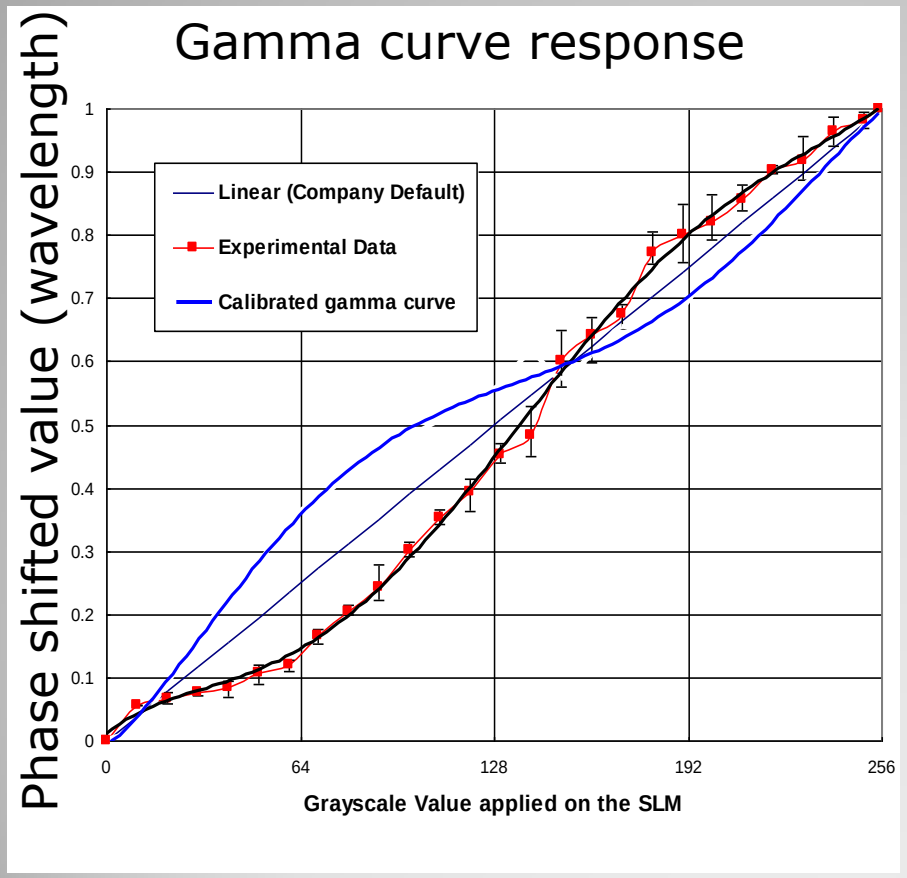
Errors when producing 1λ of tilt and corrected one after calibration





S = 0.25λ shift when 63 value applied

Corrected Gamma Curve



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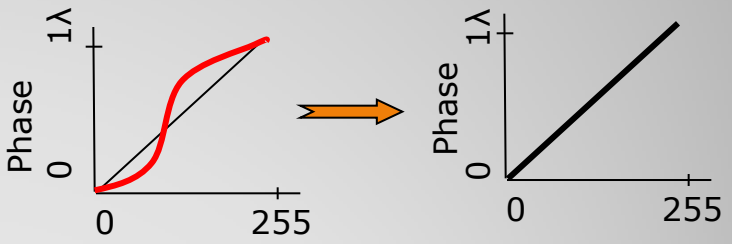
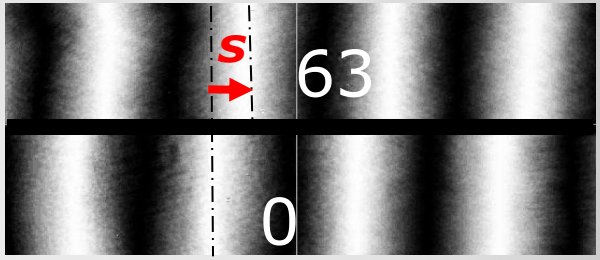




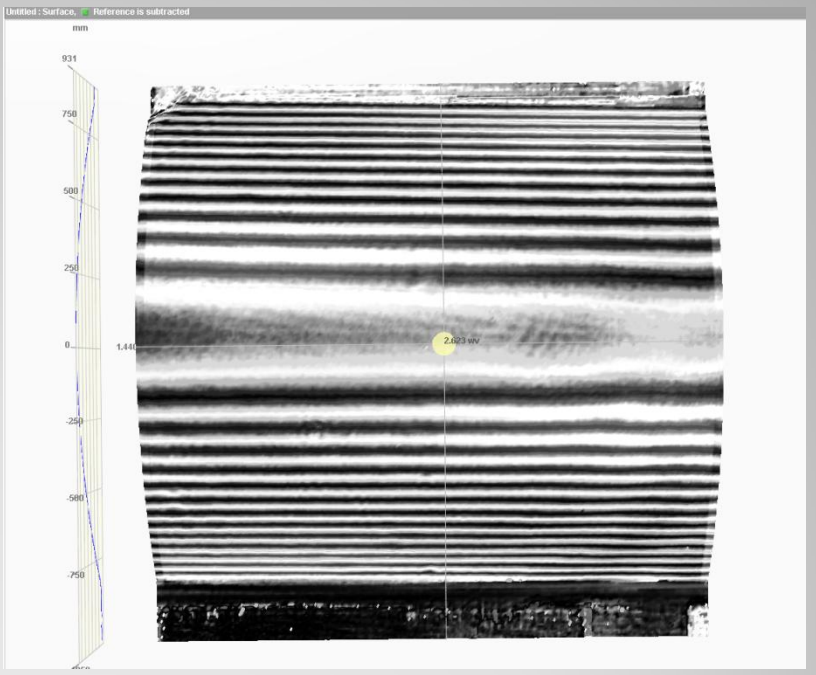
S = 0.25λ shift when 63 value applied

Producing cylindrical wavefronts

Applied Phase on the SLM

$\Phi \sim a\, y^2$
Matlab formula used to generate the phase.

Interferogram on the pixelcam

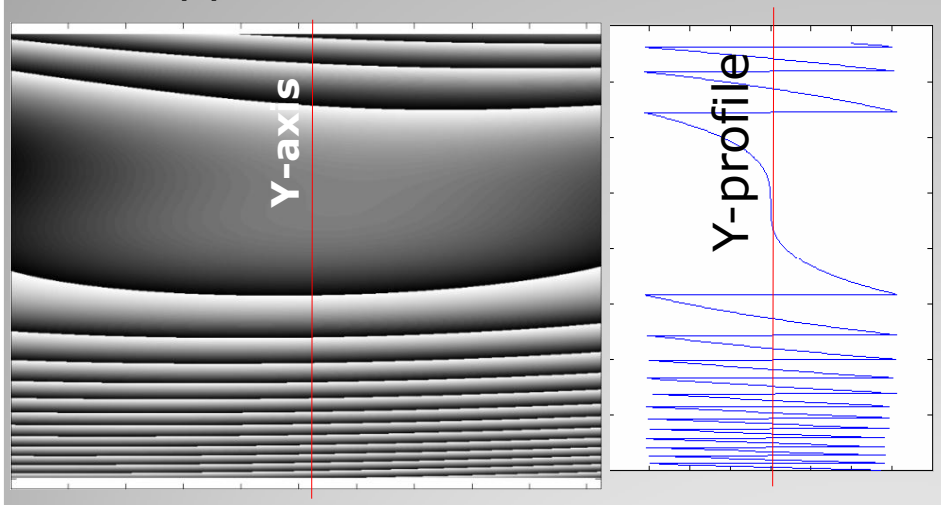


- Cylindrical wrapped phase written by Matlab code and applied on the SLM, which is good candidate compensating phase for a Mandrel.

- Phase produced and shown by the interferogram on the pixelcam

Producing arbitrary wavefronts

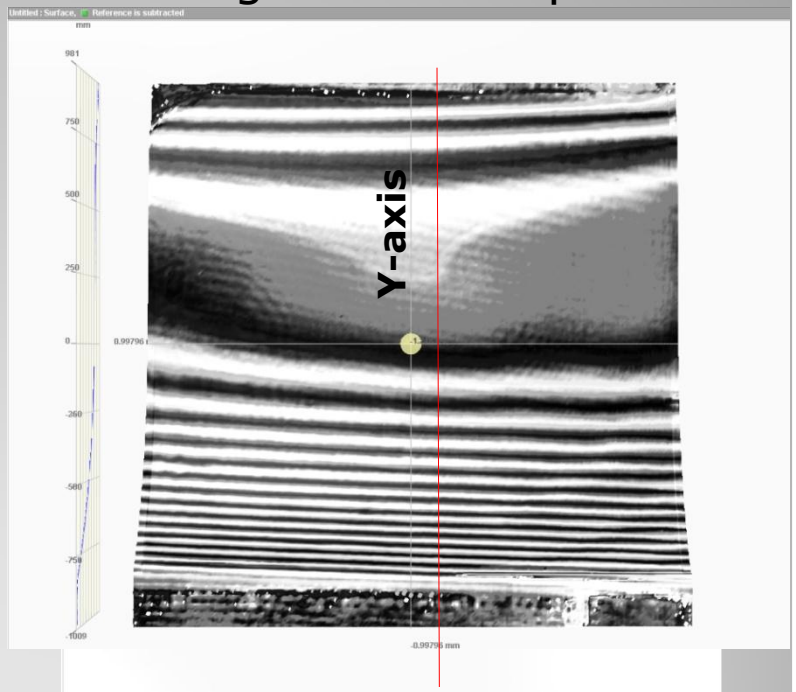
Applied Phase on the SLM



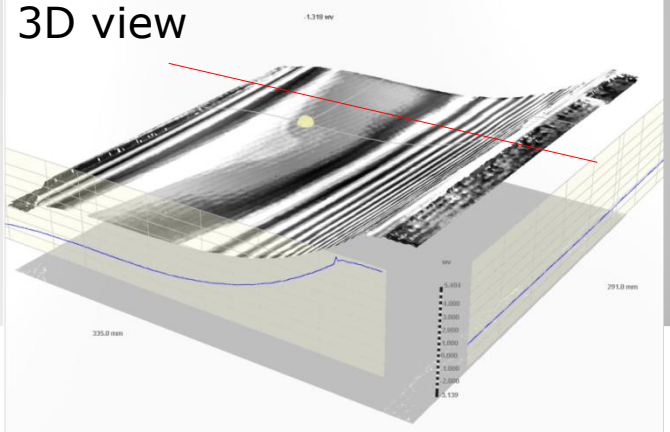
$\Phi = 20.*(y-0.25)^3 - x.^2 + x.*y + x.*y^3$
Matlab formula used to generate the phase

- Arbitrary wrapped phase written by Matlab code and applied on the SLM
- Phase produced and shown by the interferogram on the pixelcam

Interferogram on the pixelcam

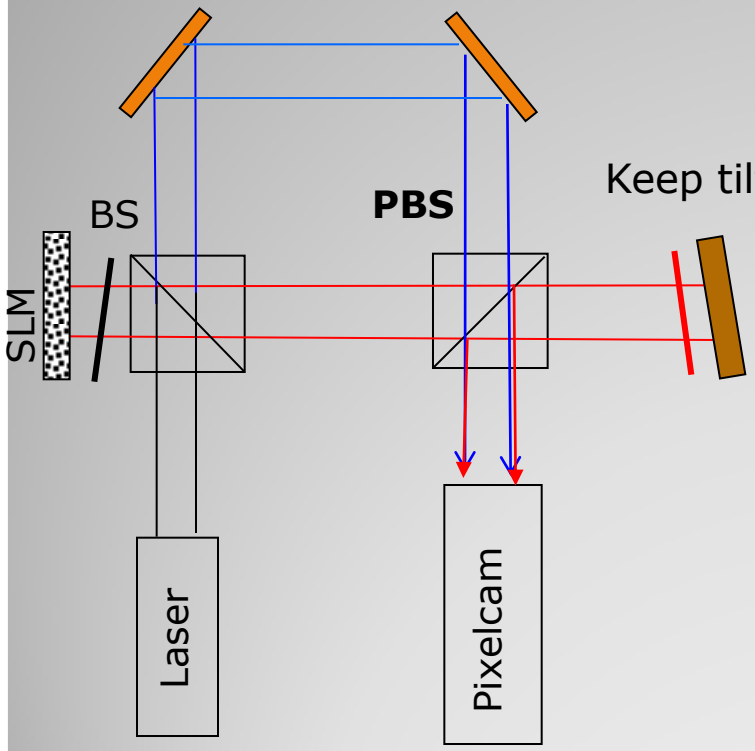


3D view



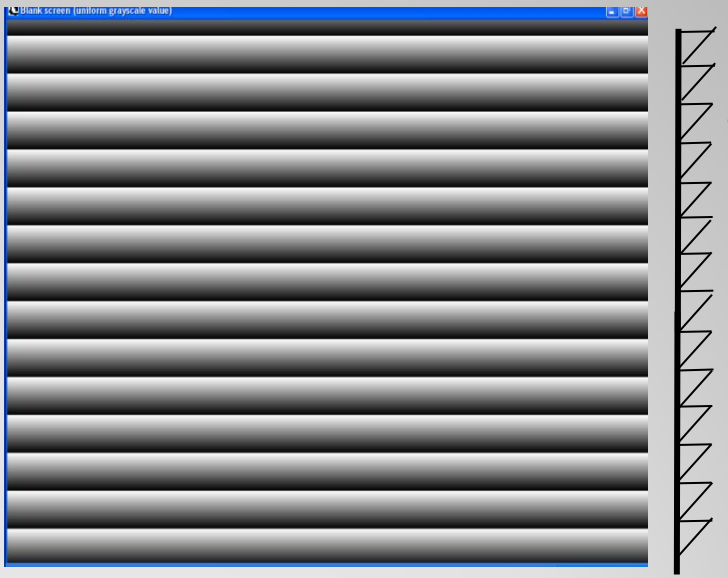
Compensation of Tilt

-Applied compensating tilt by the SLM

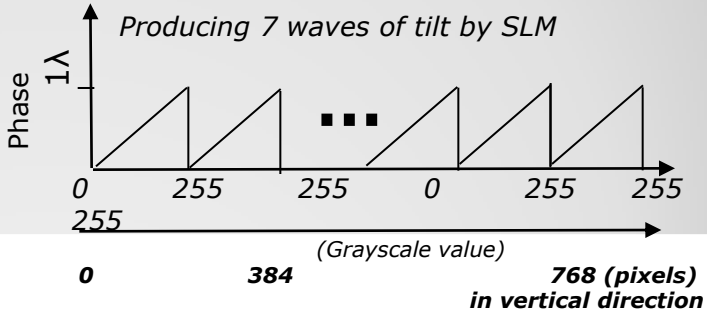


(Various waveplates and telescopes not shown)

Wrapped phase applied on the SLM

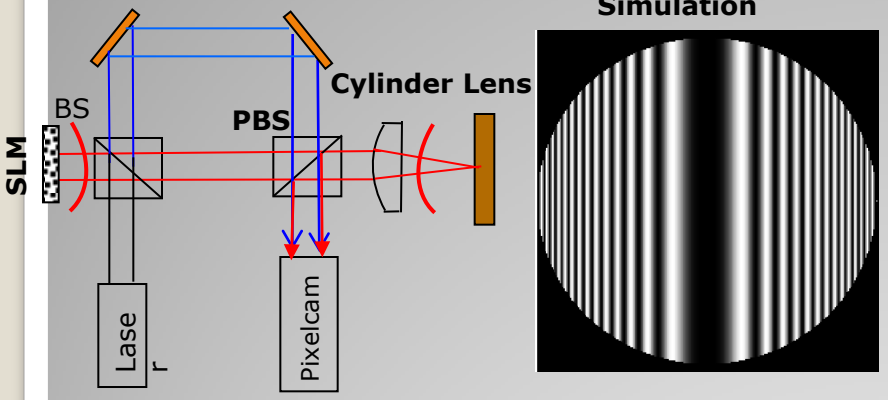


~ 14 fringes



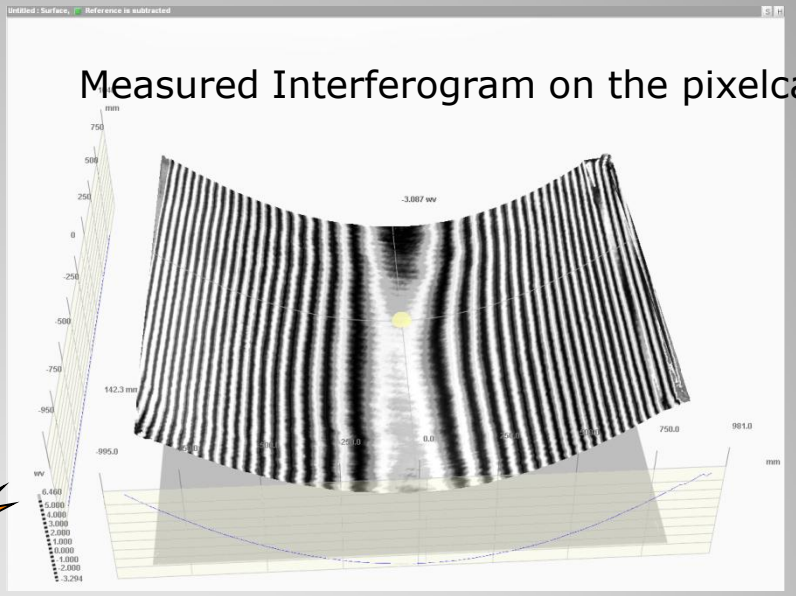
Compensating wrapped phase applied on the SLM

Compensation of Cylindrical wavefronts

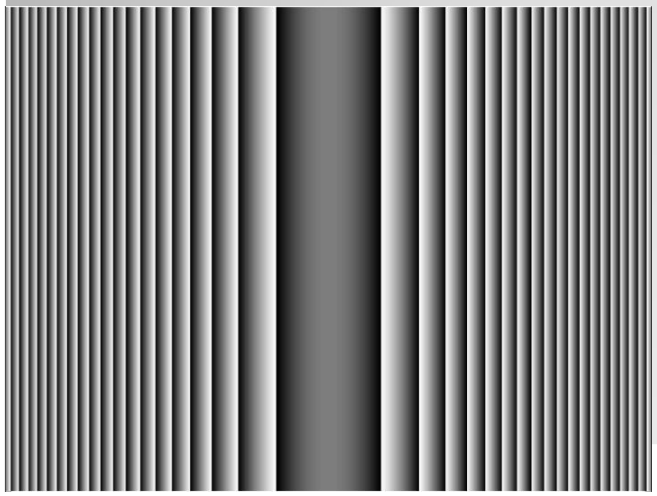


Simulation

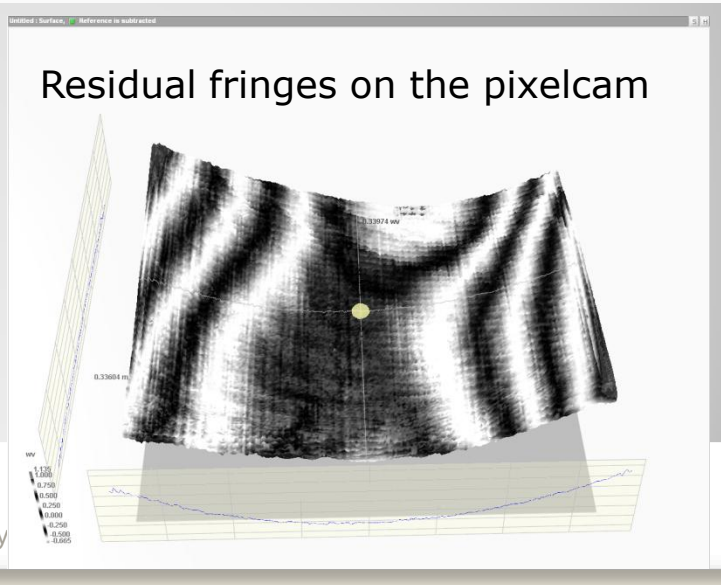
Measured Interferogram on the pixelcam



Applied Phase on the SLM

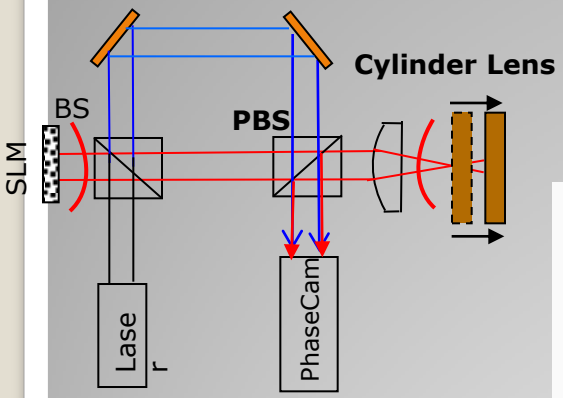


Residual fringes on the pixelcam

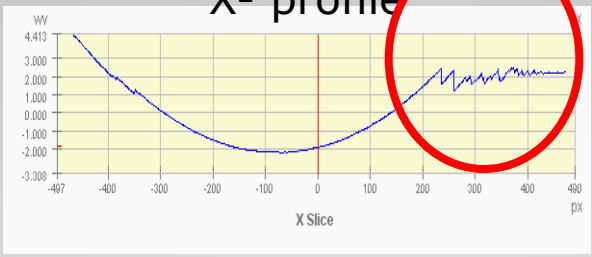


Compensation of Cylindrical wavefronts

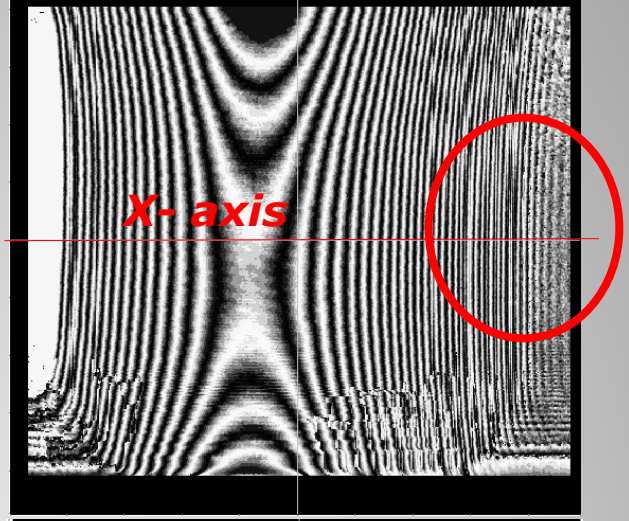
Extreme Case



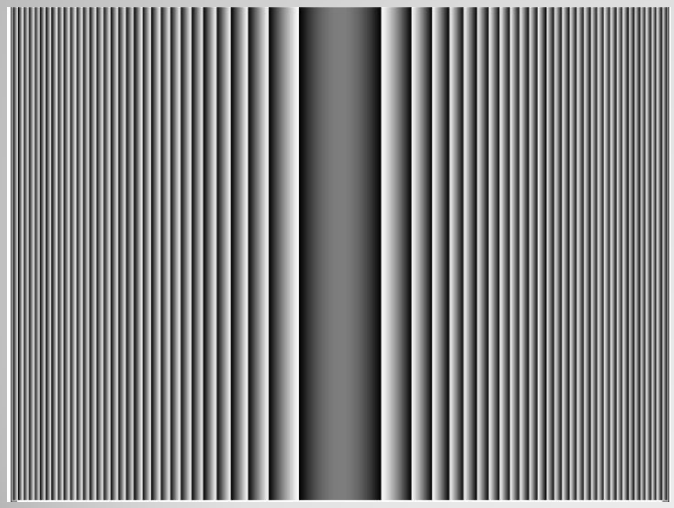
X- profile



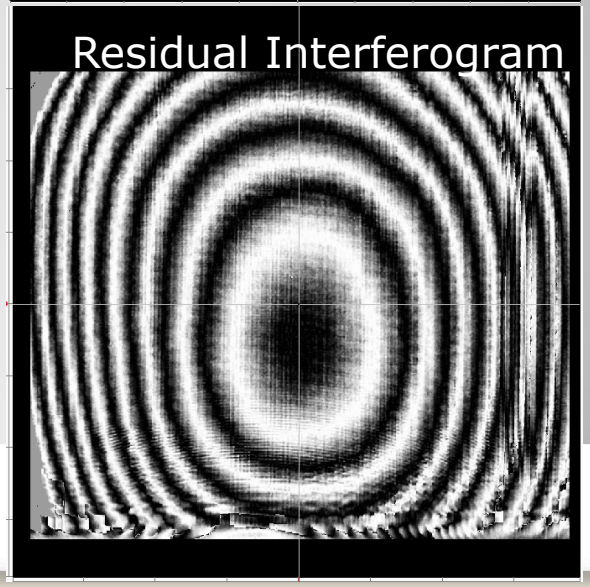
Measured Interferogram



Applied Phase on the SLM

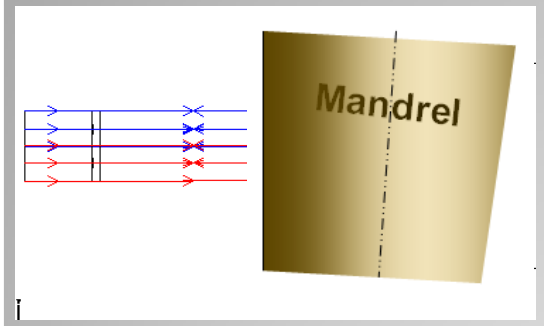


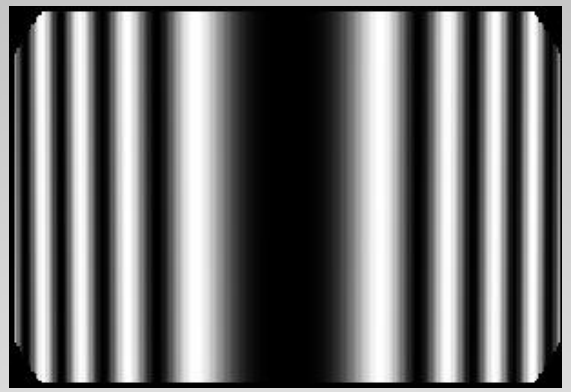
Residual Interferogram

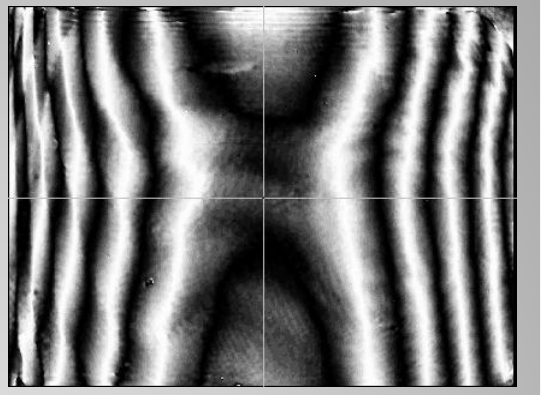


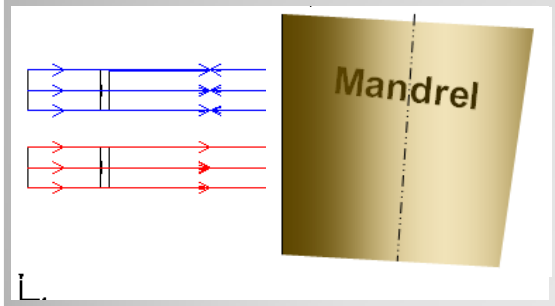
The phase on SLM is used to bring the dense fringes down into the measurement range of the pixelcam. i.e: extended dynamic range.

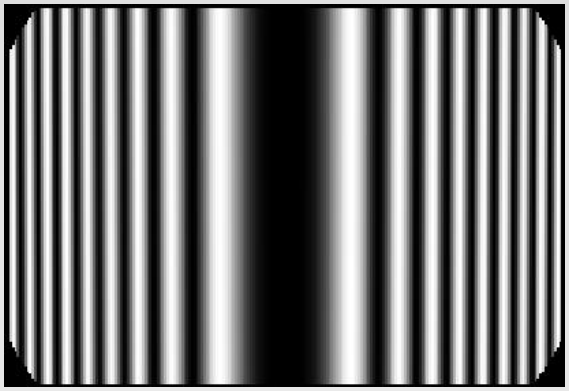
Wavefront Differences at Different Heights of Mandre

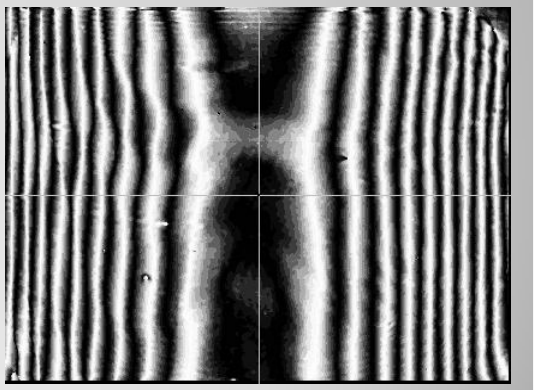












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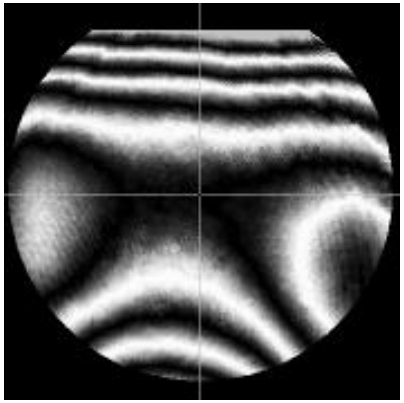

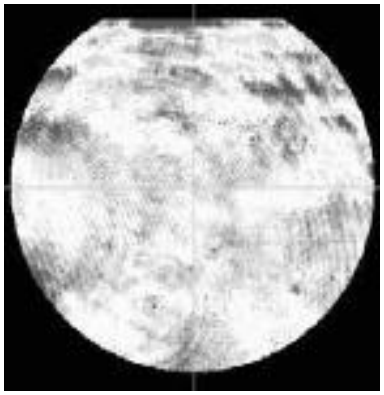

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  - Noise floor and resolutioin improvementt

SBIR Phase II contract no. NNX08CA25C Date: May, 2010
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jtrolinger@metrolaserinc.com