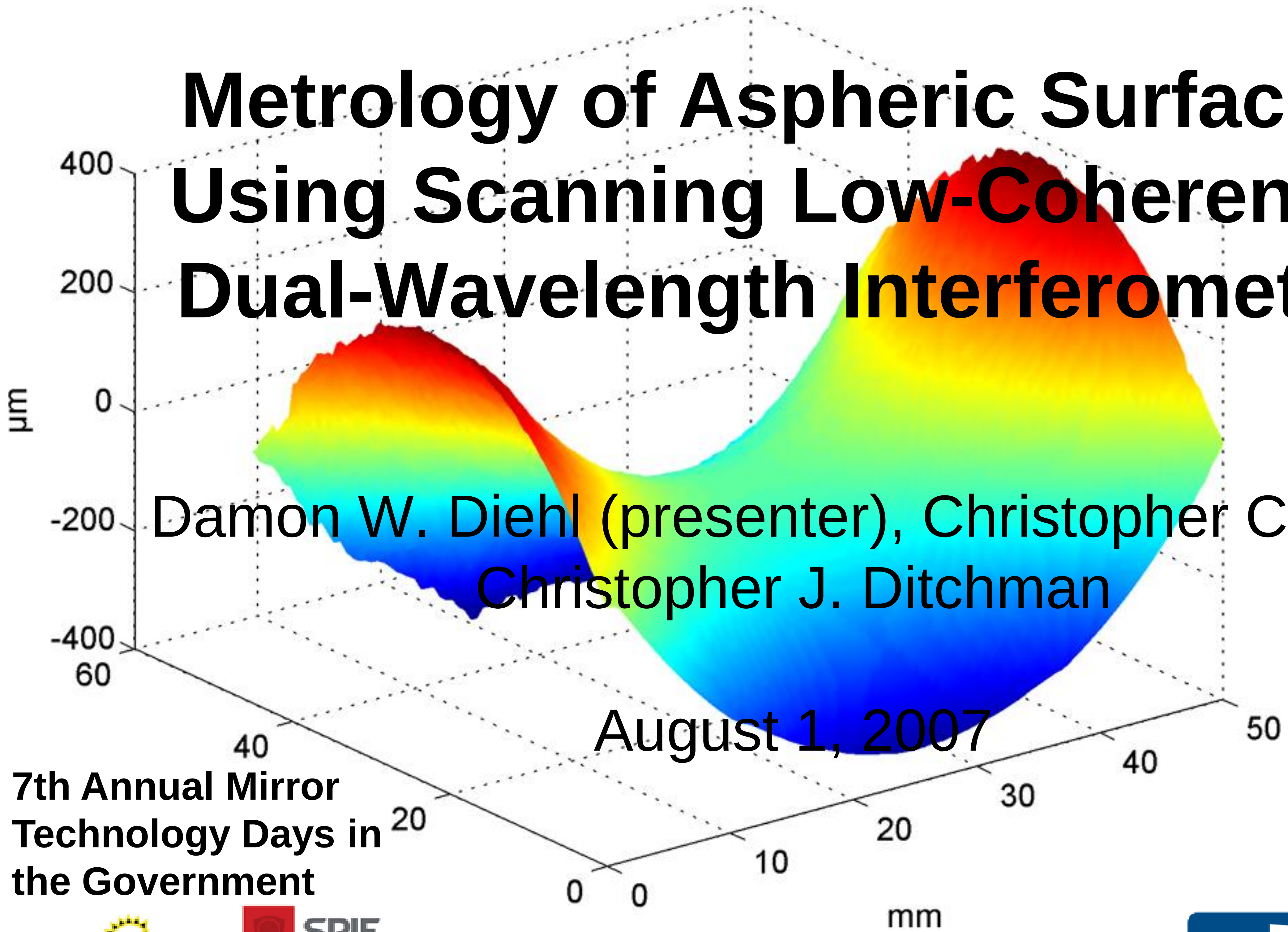
Metrology of Aspheric Surfaces Using Scanning Low-Coherence Dual-Wavelength Interferometry



Damon W. Diehl (presenter), Christopher Cotton, Christopher J. Ditchman

August 1, 2007

7th Annual Mirror Technology Days in the Government

NMOIA SPIE

ase OPTICS

Acknowledgements

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- A portion of this project was funded by US Army grant W31P4Q-06-C-0185.
- Lumetrics, Inc. provided the OptiGauge dual interferometer used for these measurements.
- Douglas Jacobs-Perkins and Steve Jacobs at the University of Rochester Laboratory for Laser Energetics provided metrology samples.

“The Big Picture”

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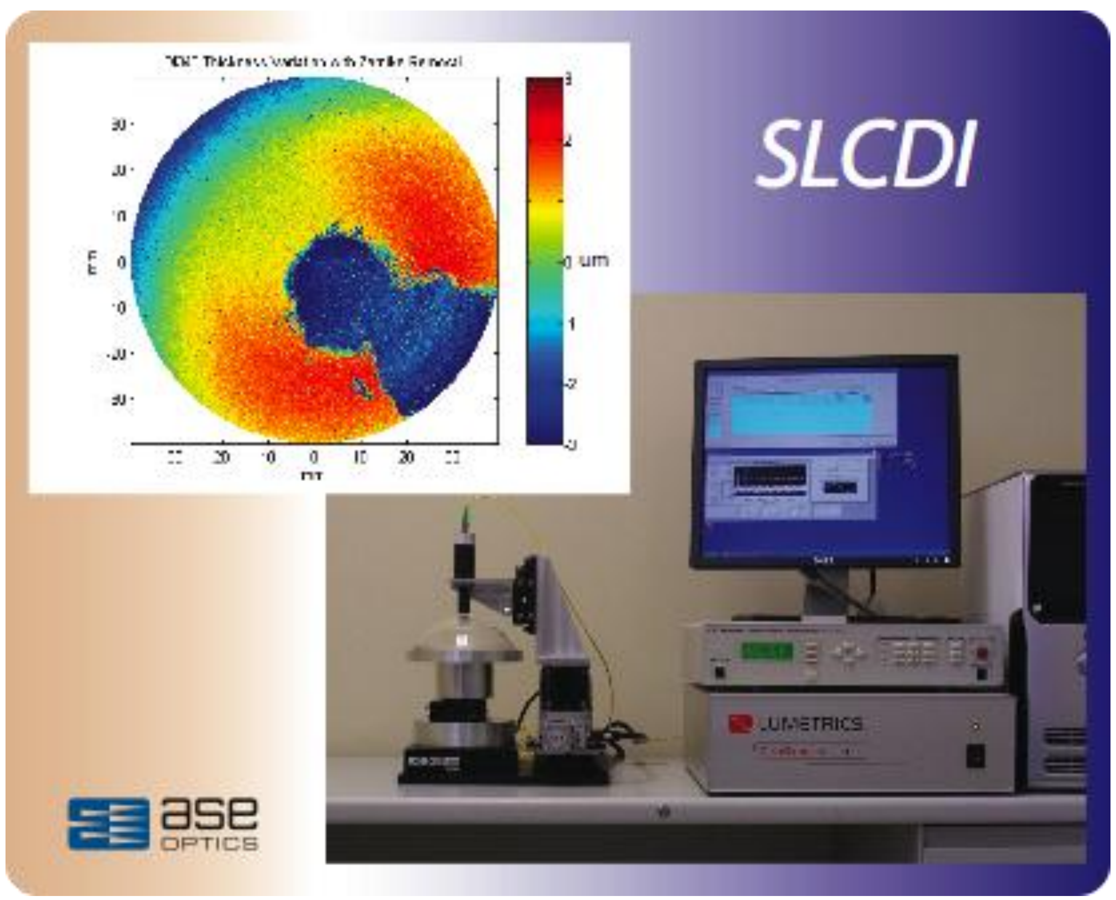
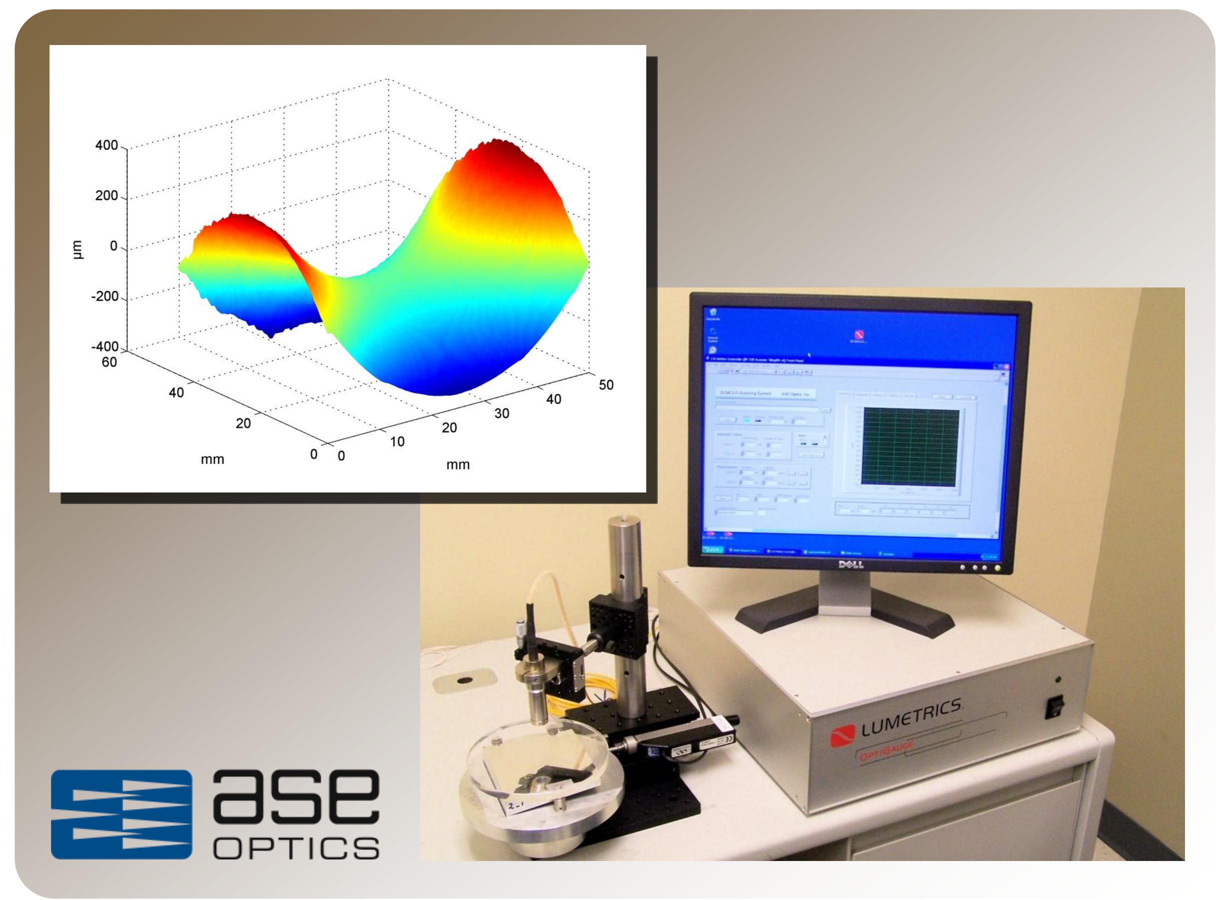
ASE Optics has developed a surface and thickness metrology instrument based upon scanning low-coherence dual-wavelength interferometry (SLCDI).

Thickness Metrology



Surface Metrology



Outline

- **Lumetrics DI Overview**
- **Hemispheric dome scanning (Army SBIR)**
- **Aspheric surface scanning (independent research)**

“Black Box” Concept

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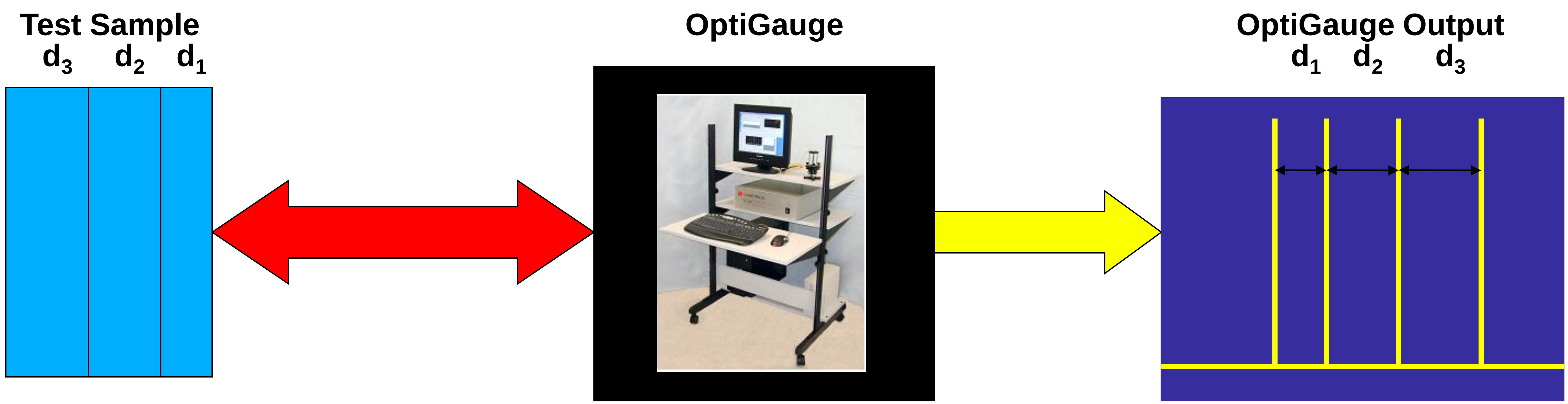
The OptiGauge uses low-coherence interferometry to simultaneously measures the thickness of each layer within a multilayer material.



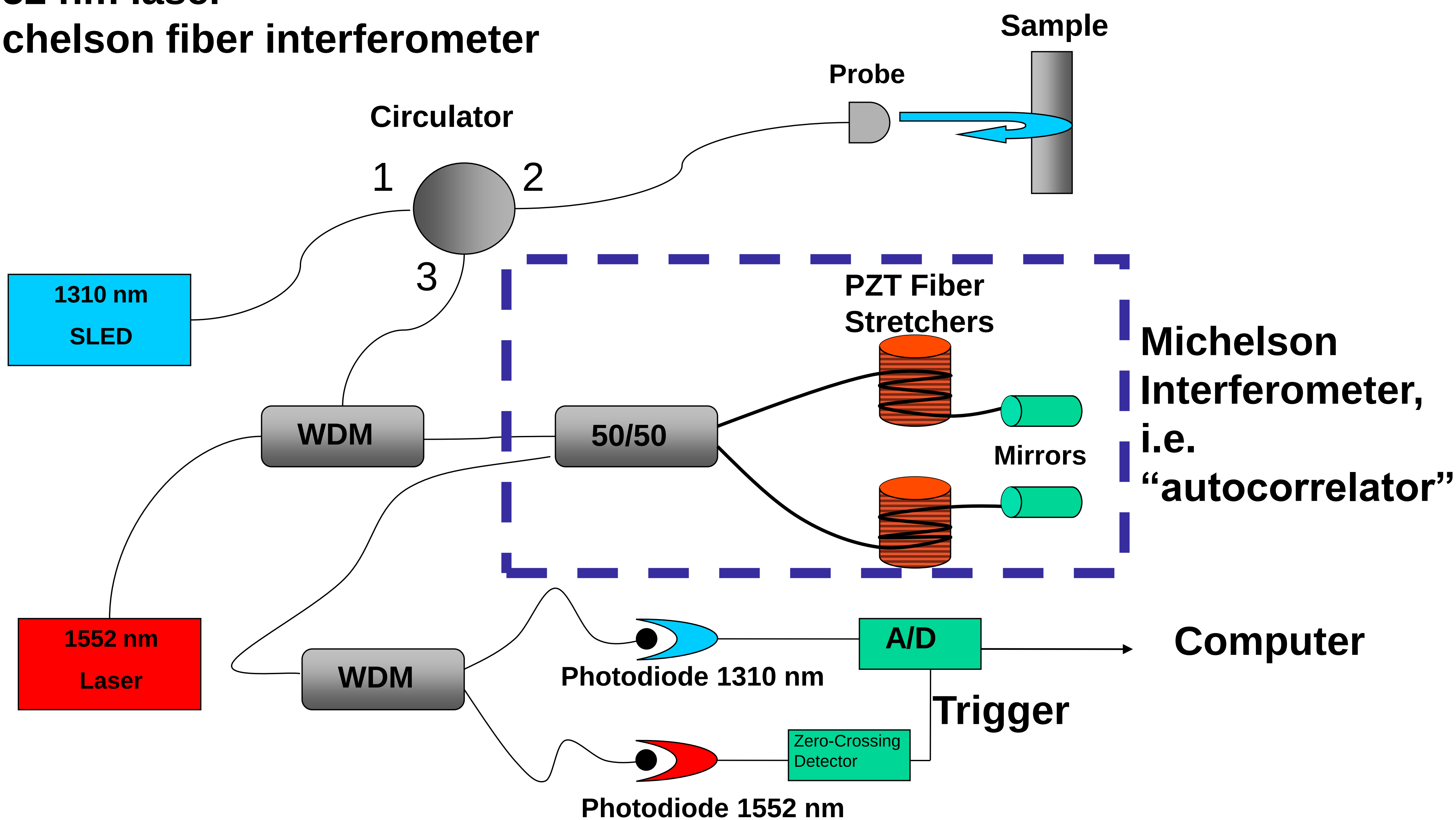
- Minimum resolution: 100 nm
- Minimum optical thickness: 12 µm
- Maximum optical thickness: 12 mm

Kodak	*Proc. SPIE* 3538, 180–191 (1999) *Proc. SPIE* 3538, 192–203 (1999) *Proc. SPIE* 4204, 61–70 (2001) *Proc. SPIE* 4578, 136–144 (2002) *Proc. SPIE* 5272, 150–156 (2003)
LUMETRICS	*Proc. SPIE* 5879, 23–41 (2005)
ase OPTICS	*Proc. SPIE* 6545 (2007)

Insided the "Black Box"

The key components inside the OptiGauge are:

- 1310 nm SLED
- 1552 nm laser
- Michelson fiber interferometer



The OptiGauge DI 340 incorporates the data analysis into a simple graphic user interface.

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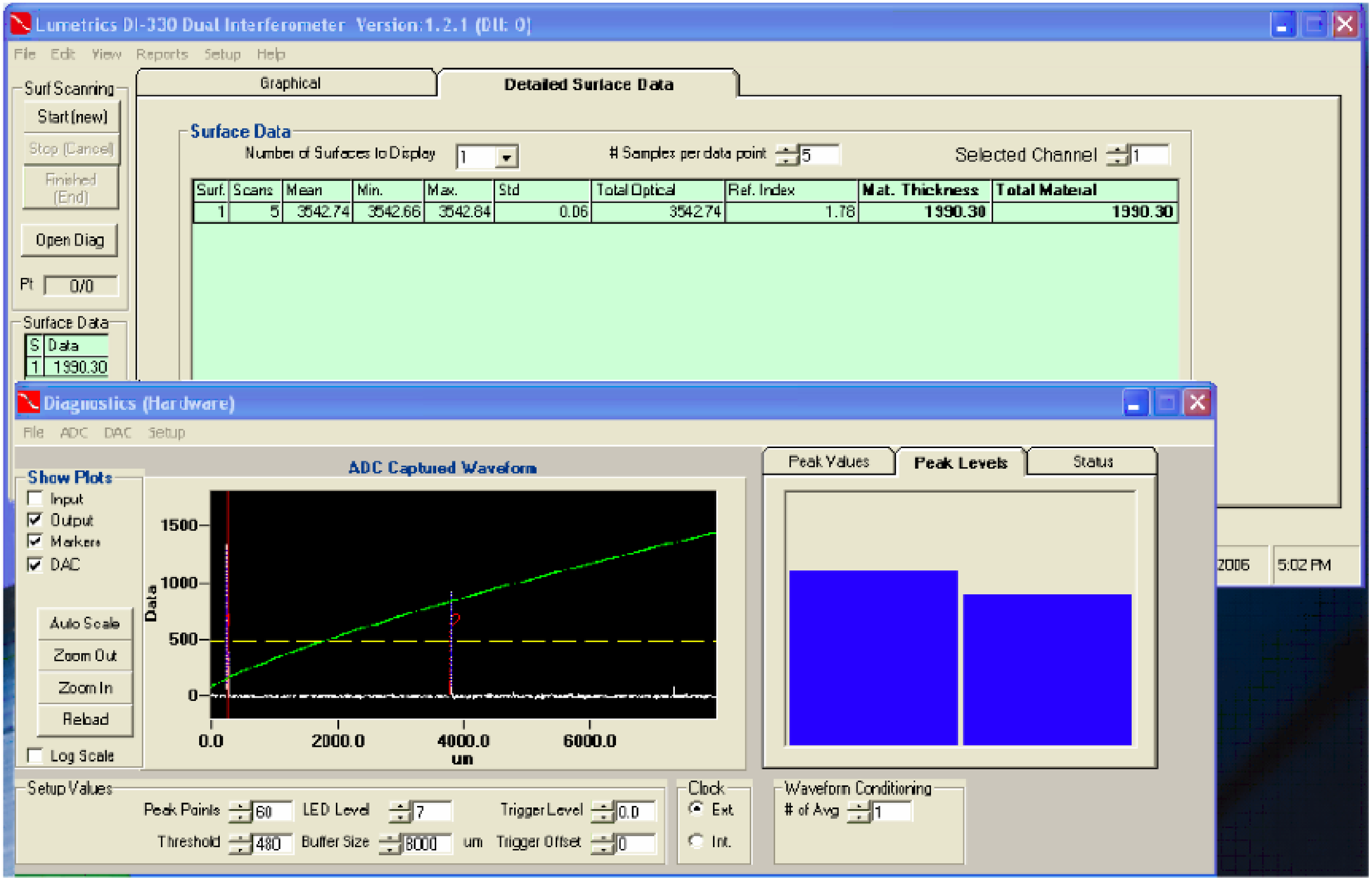

The OptiGauge probe can tolerate a ±2° surface deviation from normal.

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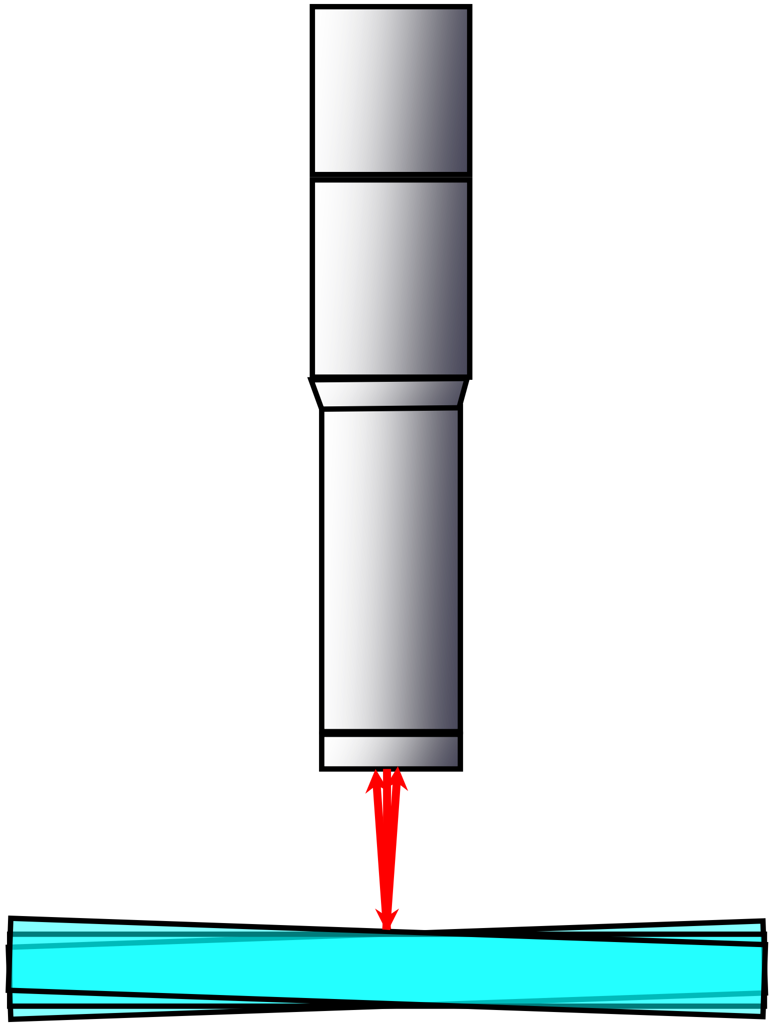

This tolerance allows the system to measure objects that differ significantly from planar or spherical without requiring complex conformal tracing.

Outline

- Lumetrics DI Overview
- Hemispheric dome scanning (Army SBIR)
- Aspheric surface scanning (independent research)

Scanner Overview:

Scanner Components

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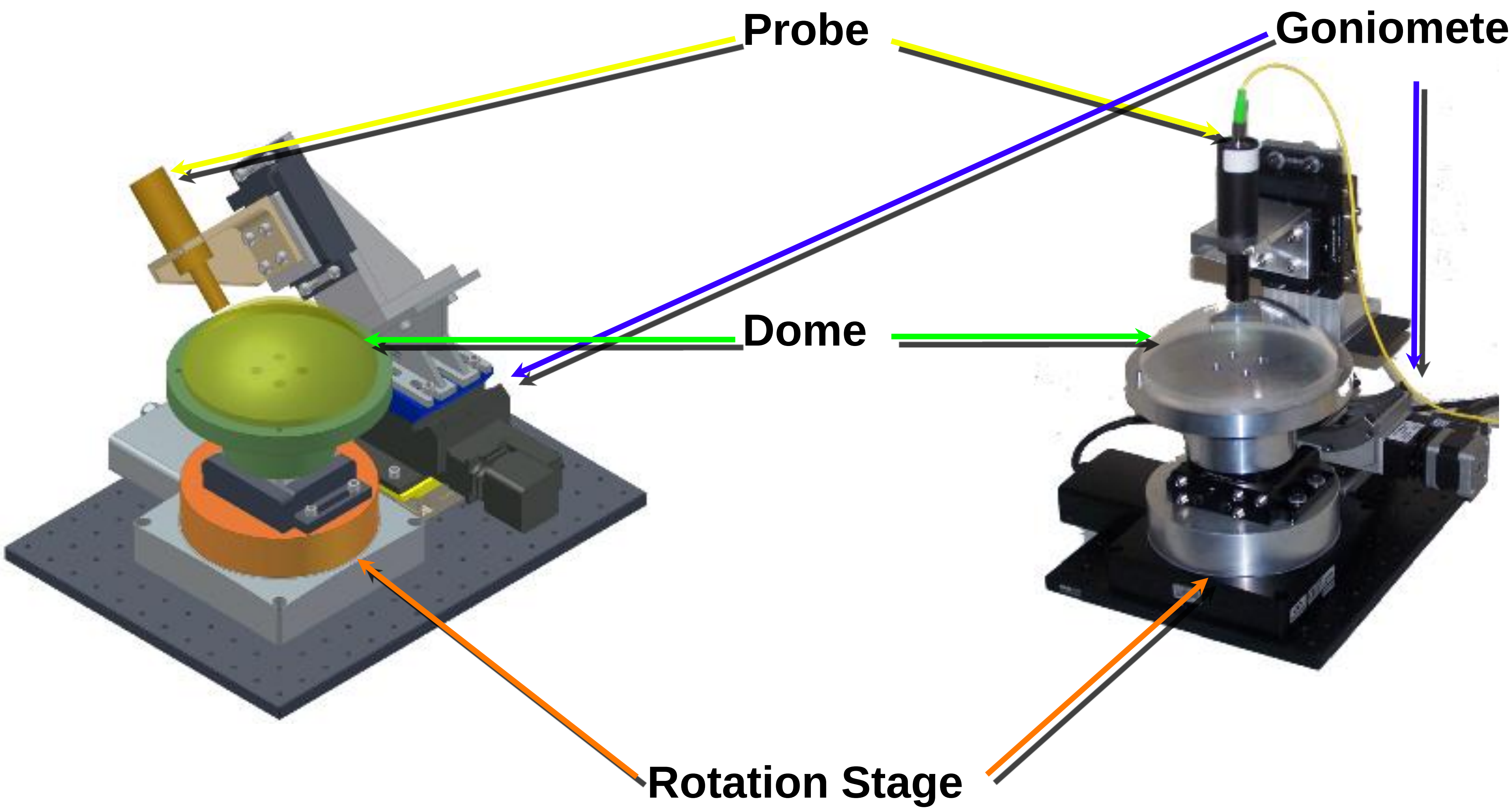

The rotation stage and goniometer allow us to scan the dome surface conformally with the probe at normal incidence.

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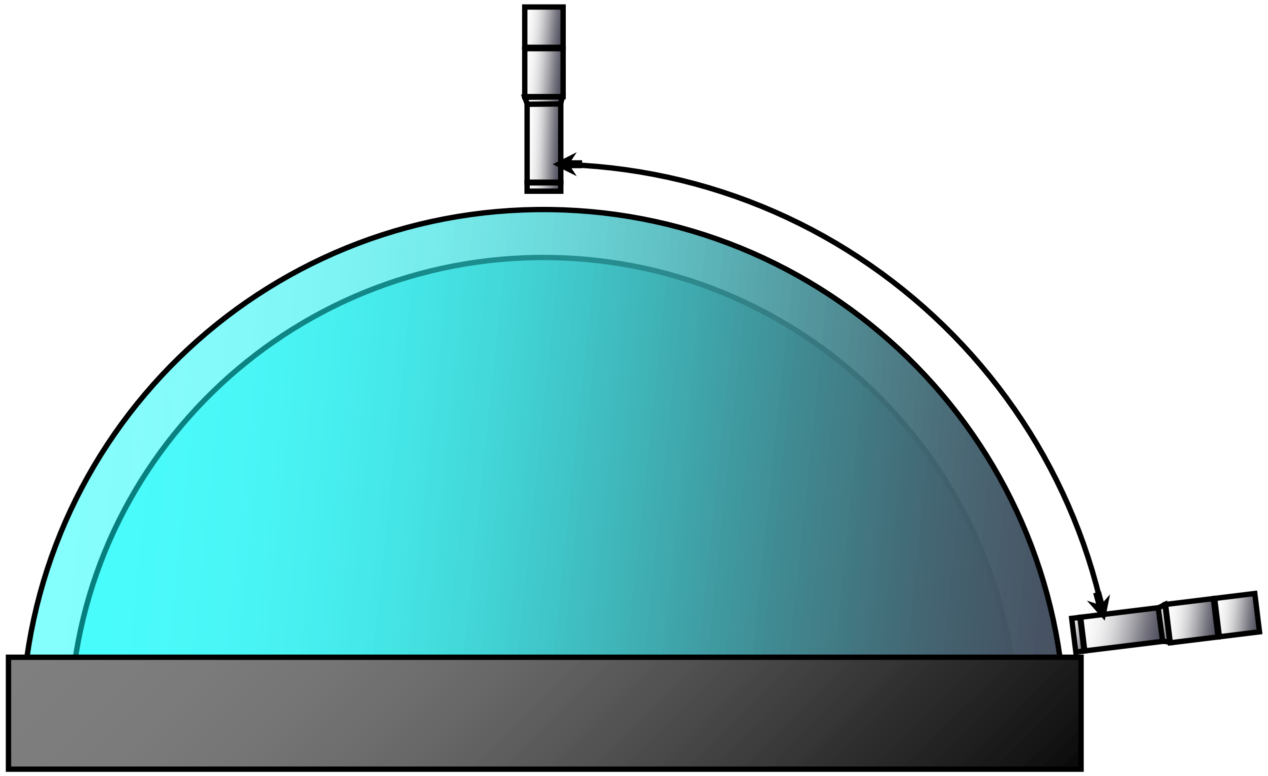

A 3.5” BK7 domelet was tested using both SLCDI & a Zygo interferometer.

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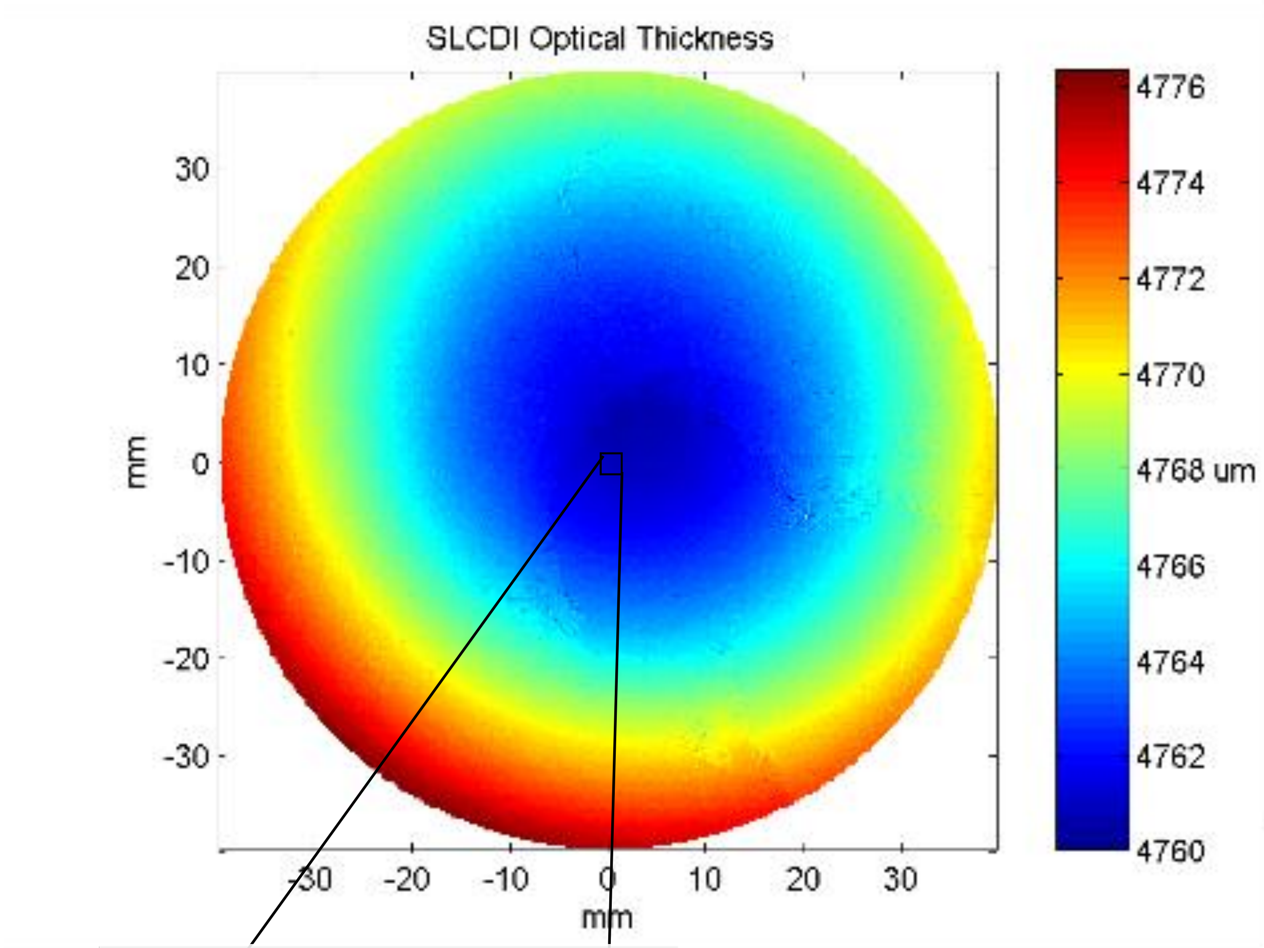
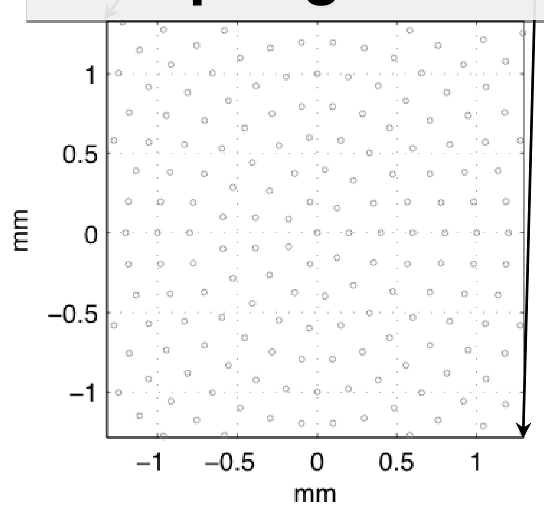
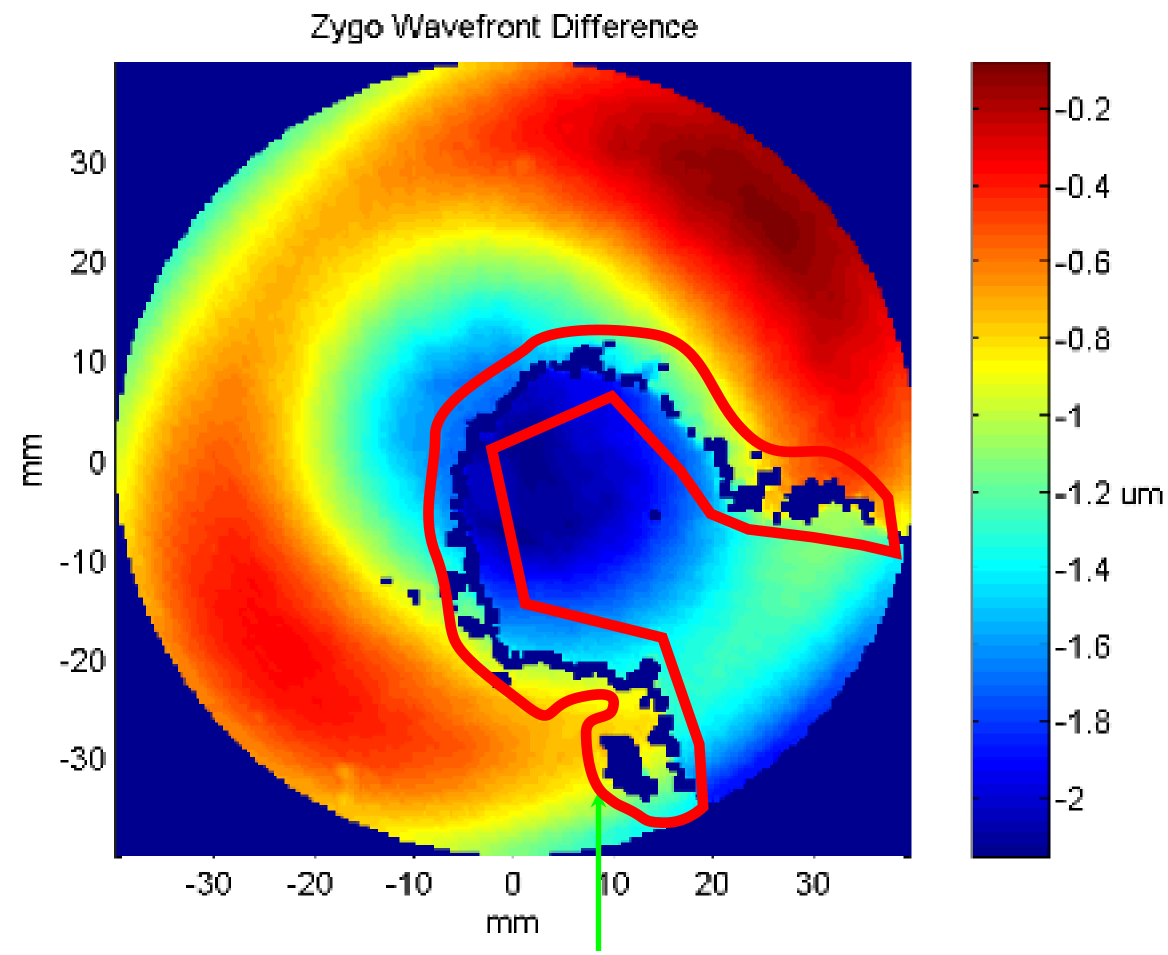


Sampling Pattern



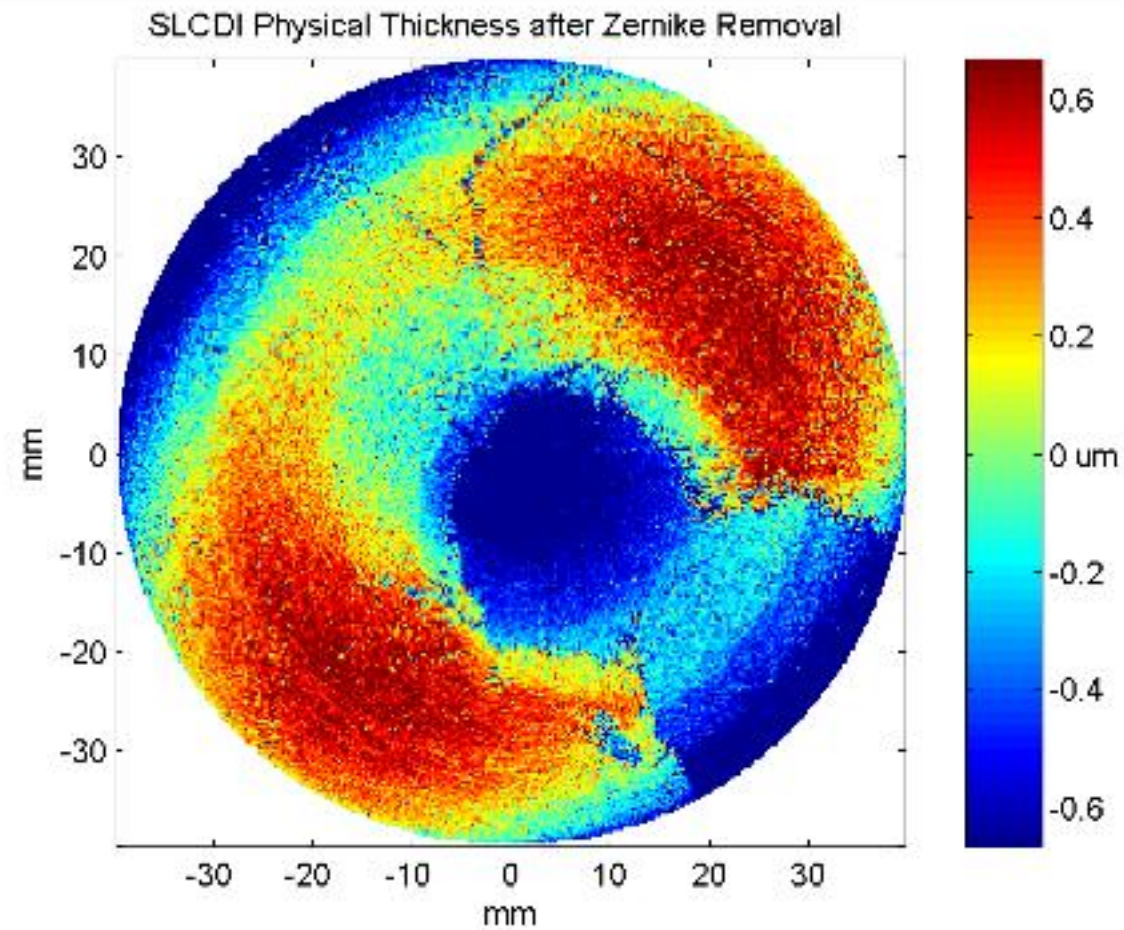
Sample Separation: 200 µm

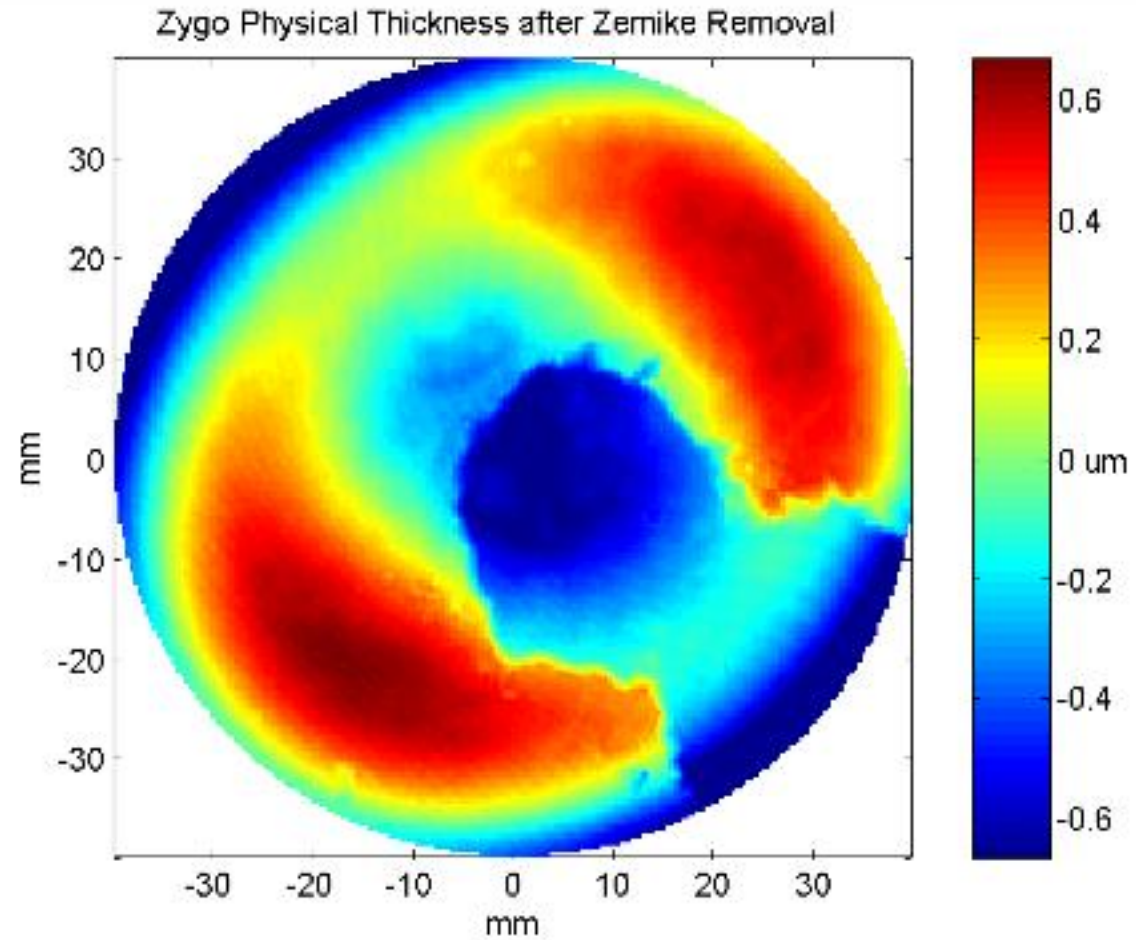


Phase unwrapping fails at discontinuities

Note: The Zygo system is aligned to remove tip/tilt and defocus.

The images can be compared by converting both maps to physical thickness and remove piston, tip/tilt, and defocus.





Zernike Order		Fit Coefficients (µm)	
		SLCDI	Zygo
0	Piston	+4811.0	-0.946
1	Tip	-0.4	+0.059
2	Tilt	-0.8	-0.132
3	Defocus	+0.8	+0.284

Nearest-neighbor averaging reduces the noise in the SLCDI image.

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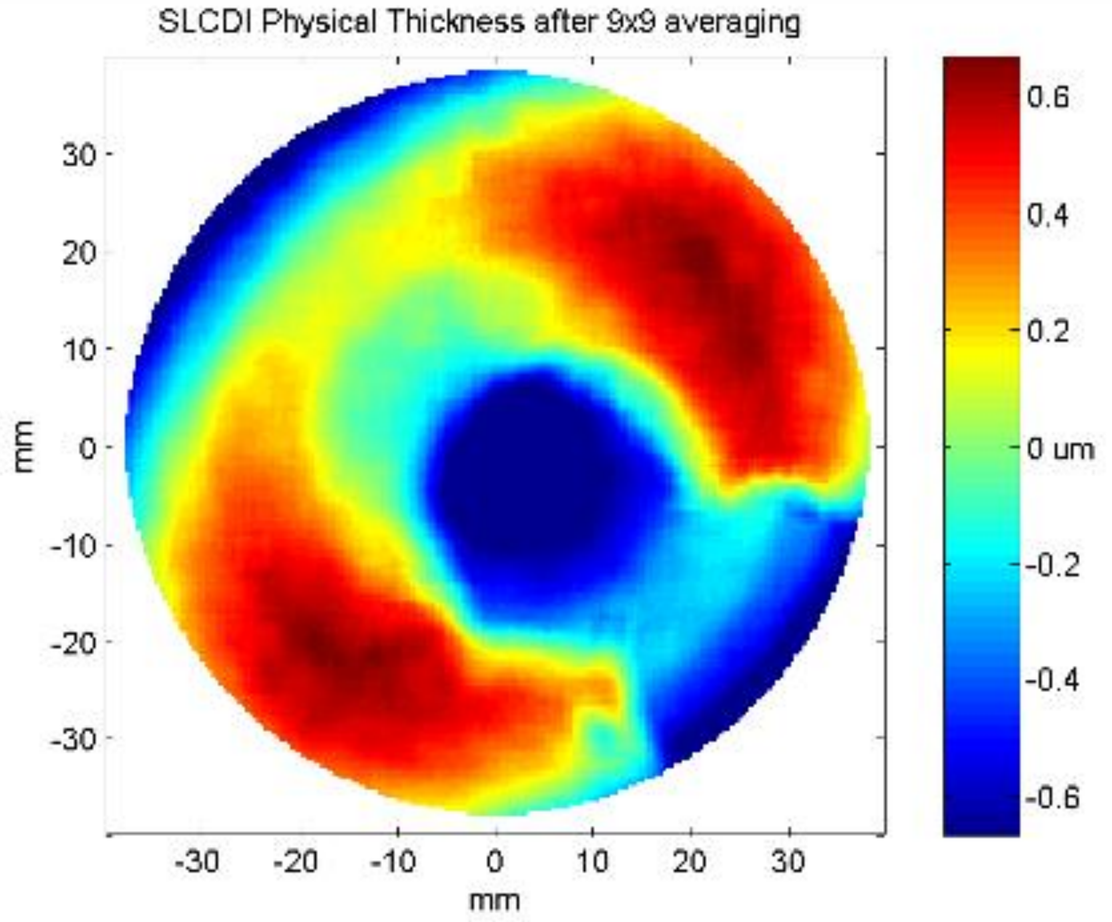
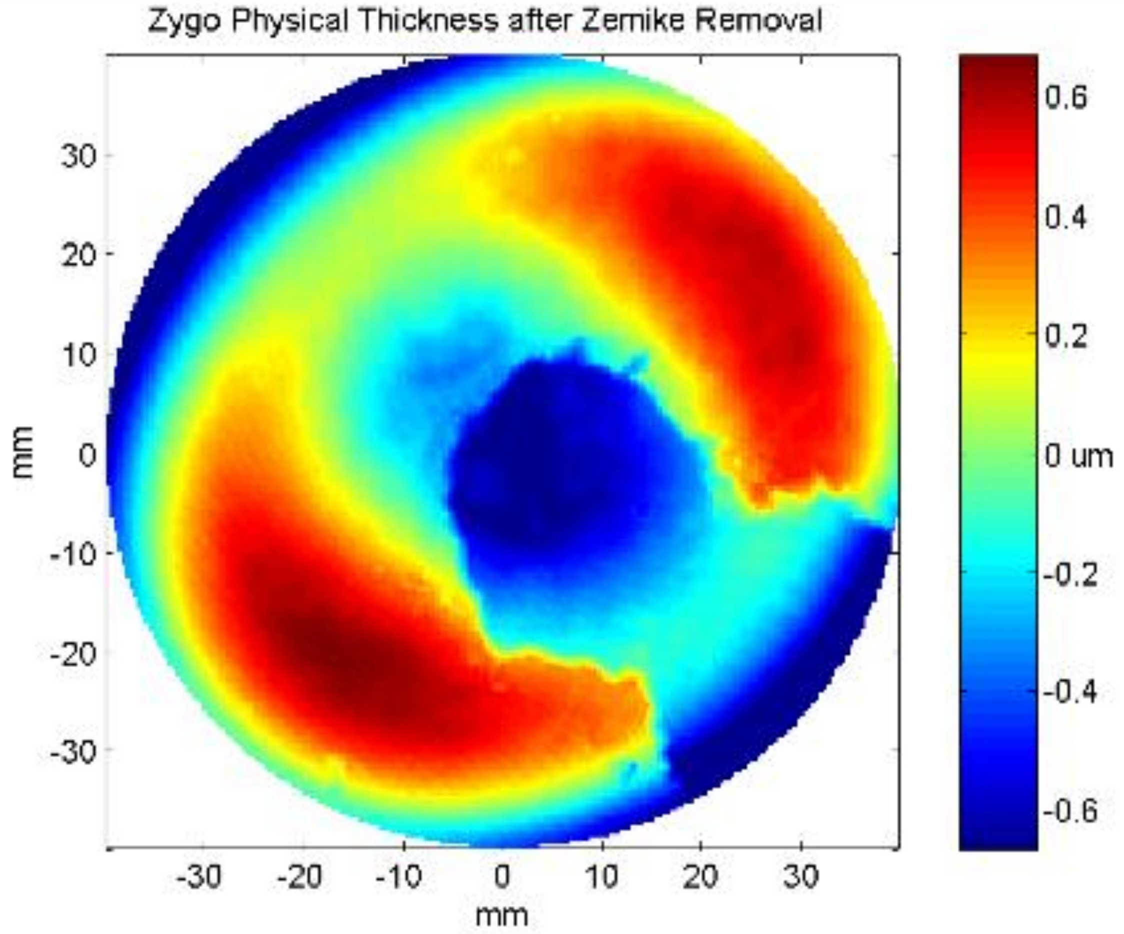
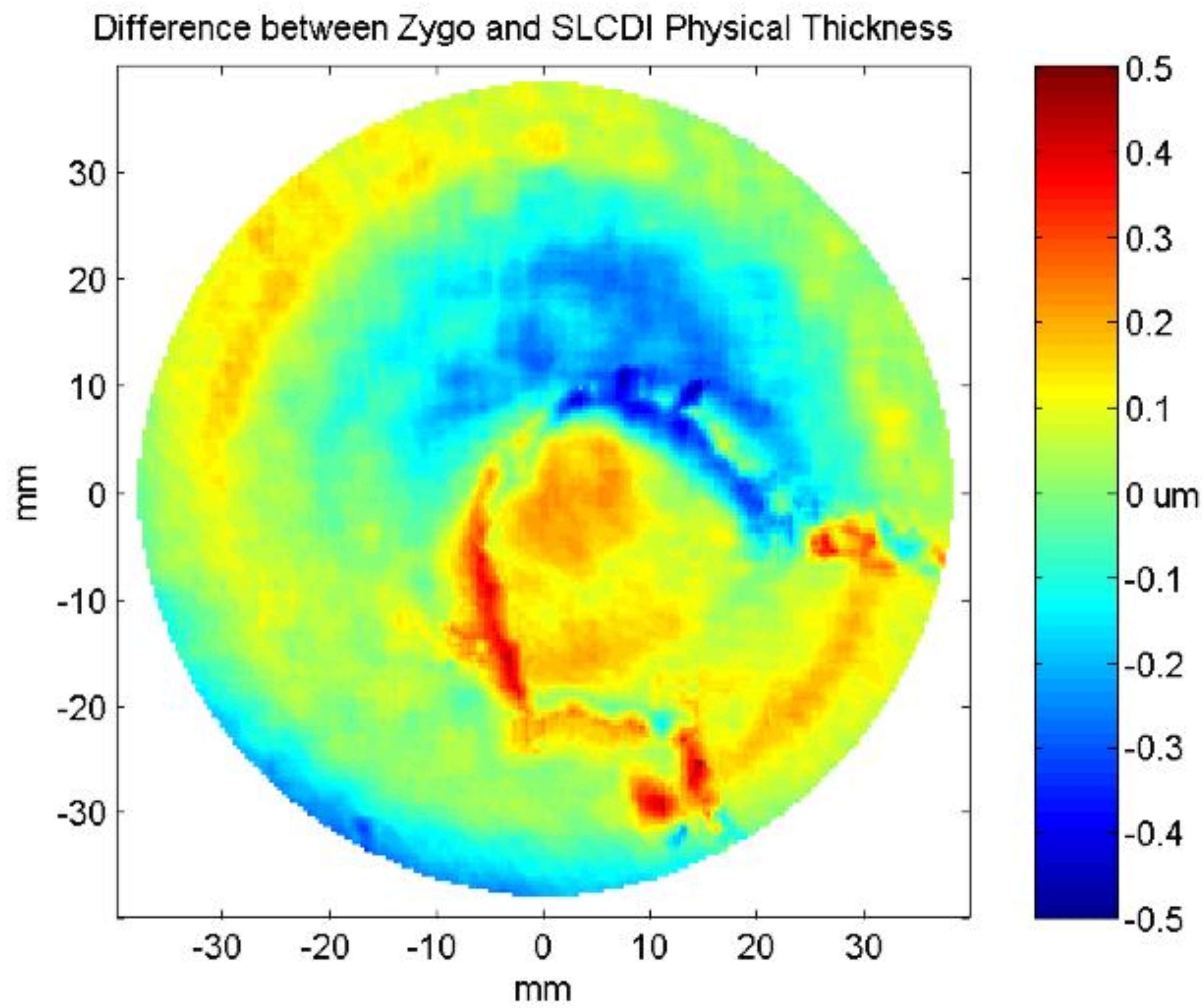




The maximum difference between the Zygo and SLCDI data is 200 nm, when disregarding the edge of the coating defect.



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Scanner Overview:

Scanner Components

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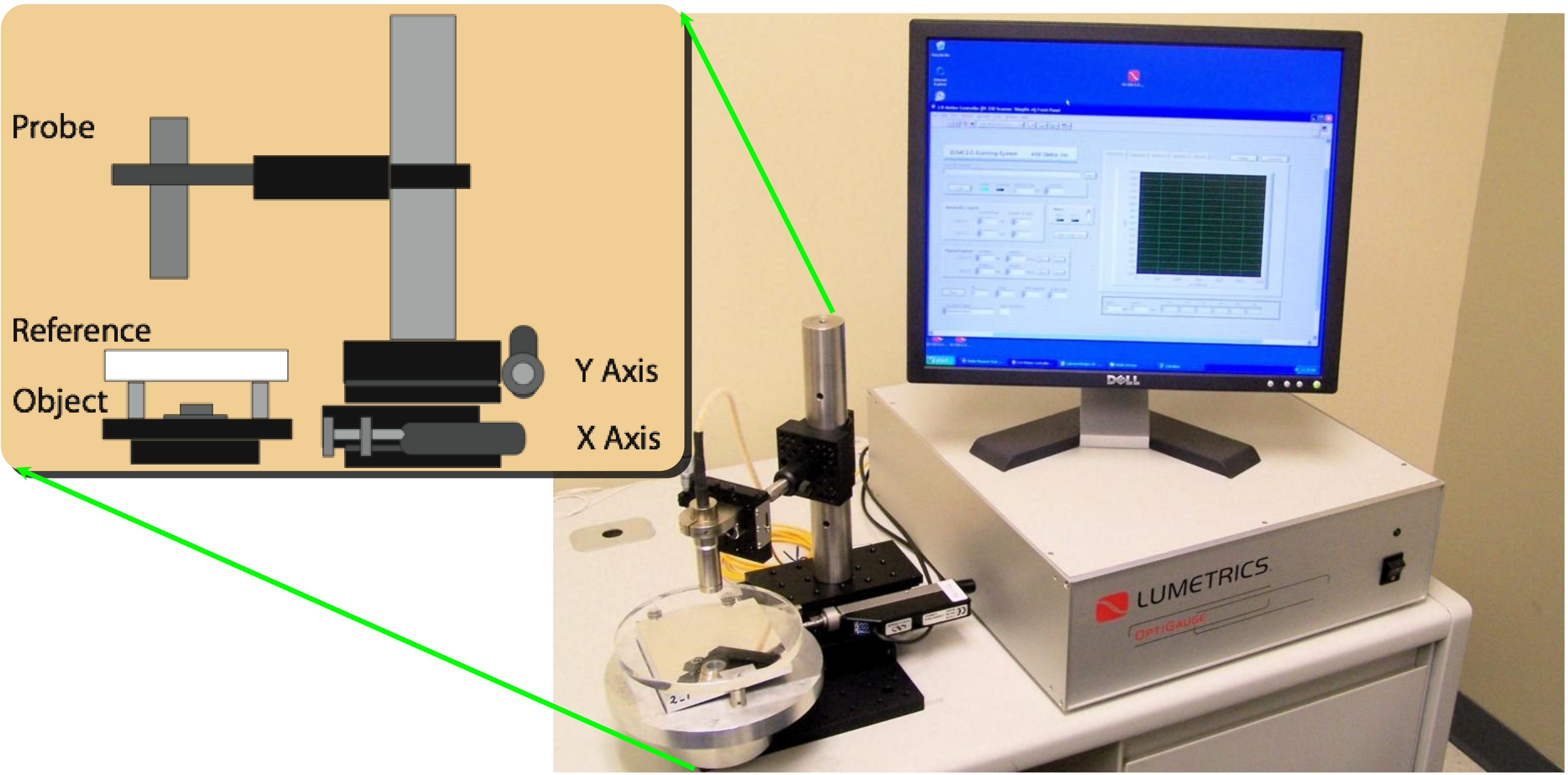

The scanner incorporates two Newport LTA-HS motorized linear stages with 0.035 µm resolution.

SLCDI measures surface profiles by measuring the airgap between a reference and a test optic.

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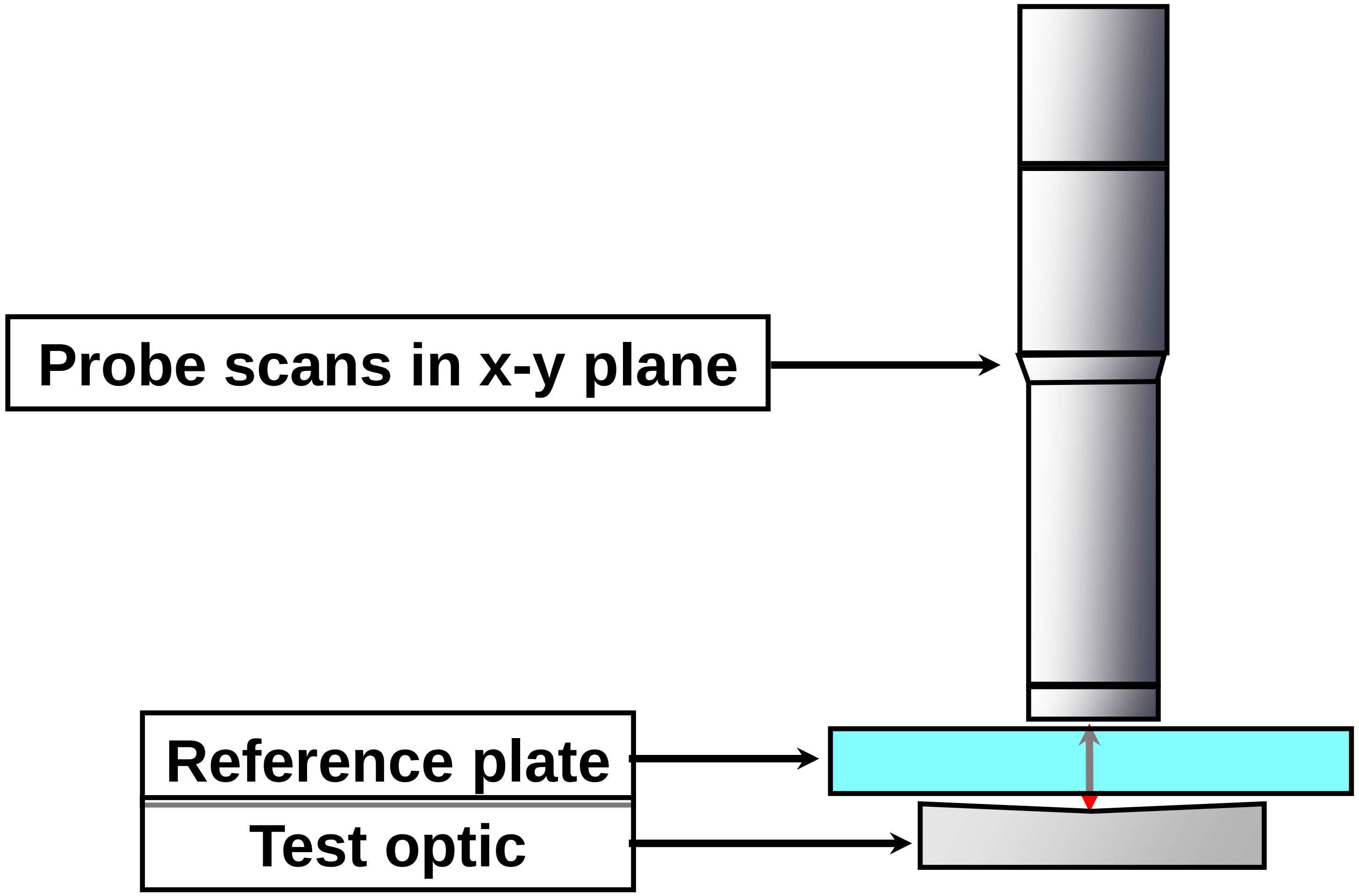

Results:

We measured a 50 mm square portion of a biconic mirror with radii of 799.5 mm and -759.23 mm.

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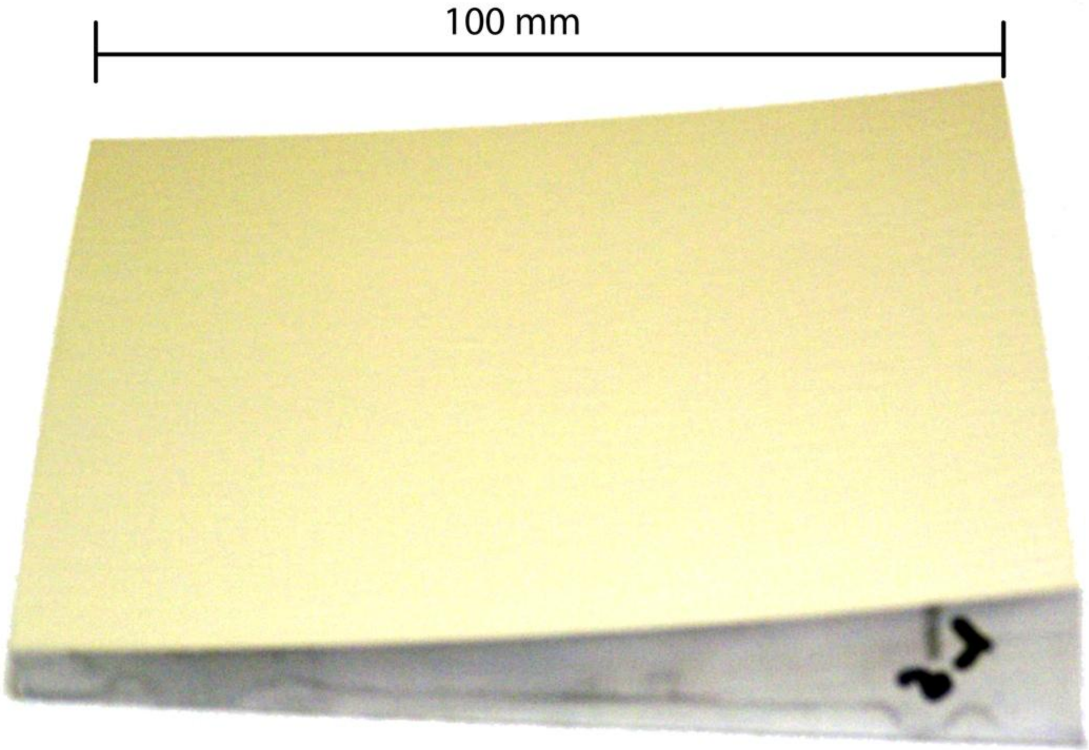
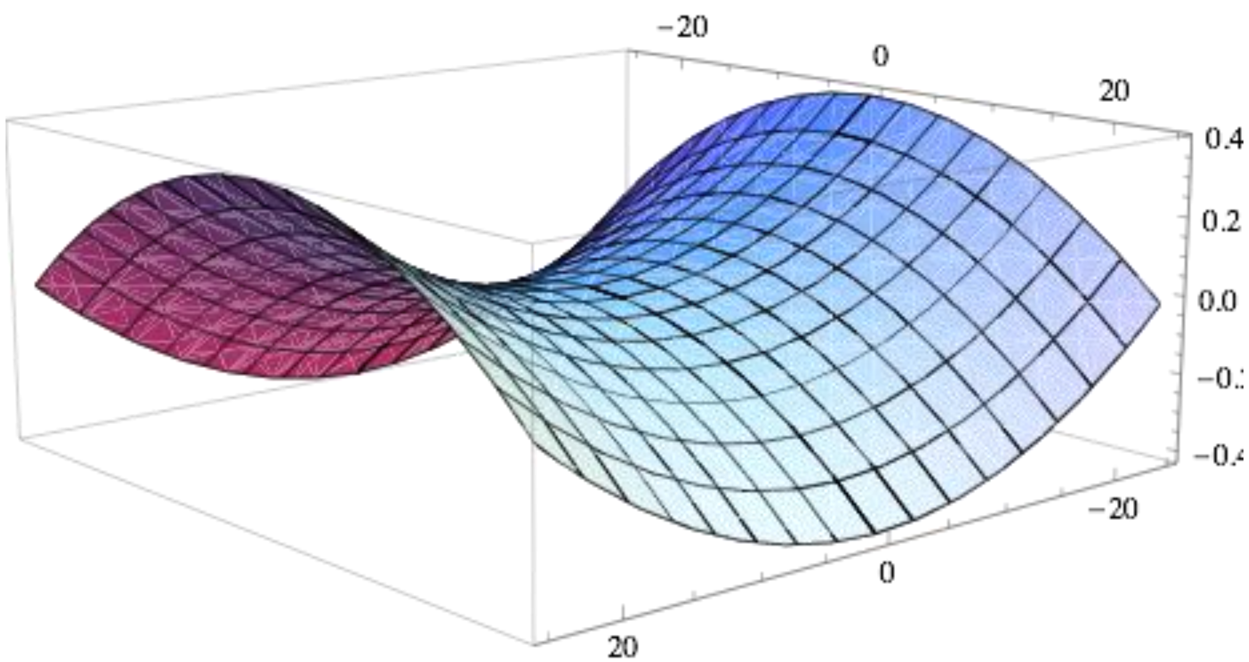
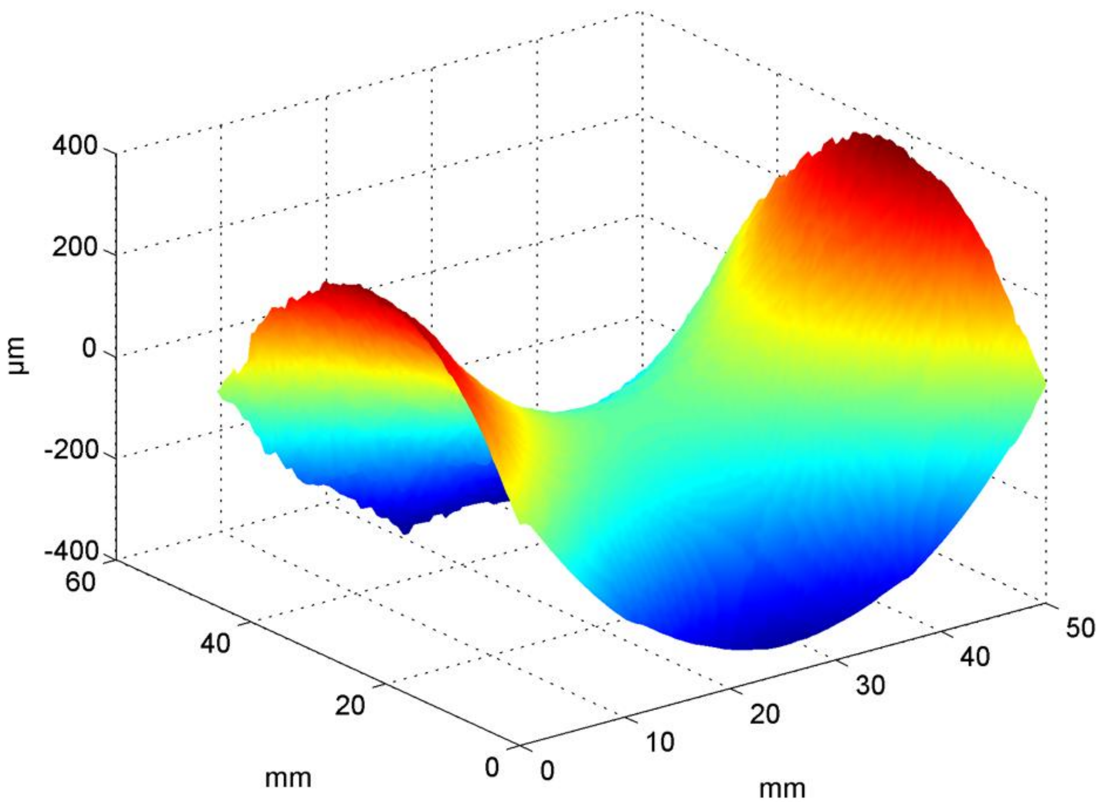




SLCDI surface profile after removal of tip/tilt



50 µm spatial resolution

Results:

SLCDI can measure discontinuous surfaces without encountering phase ambiguities.

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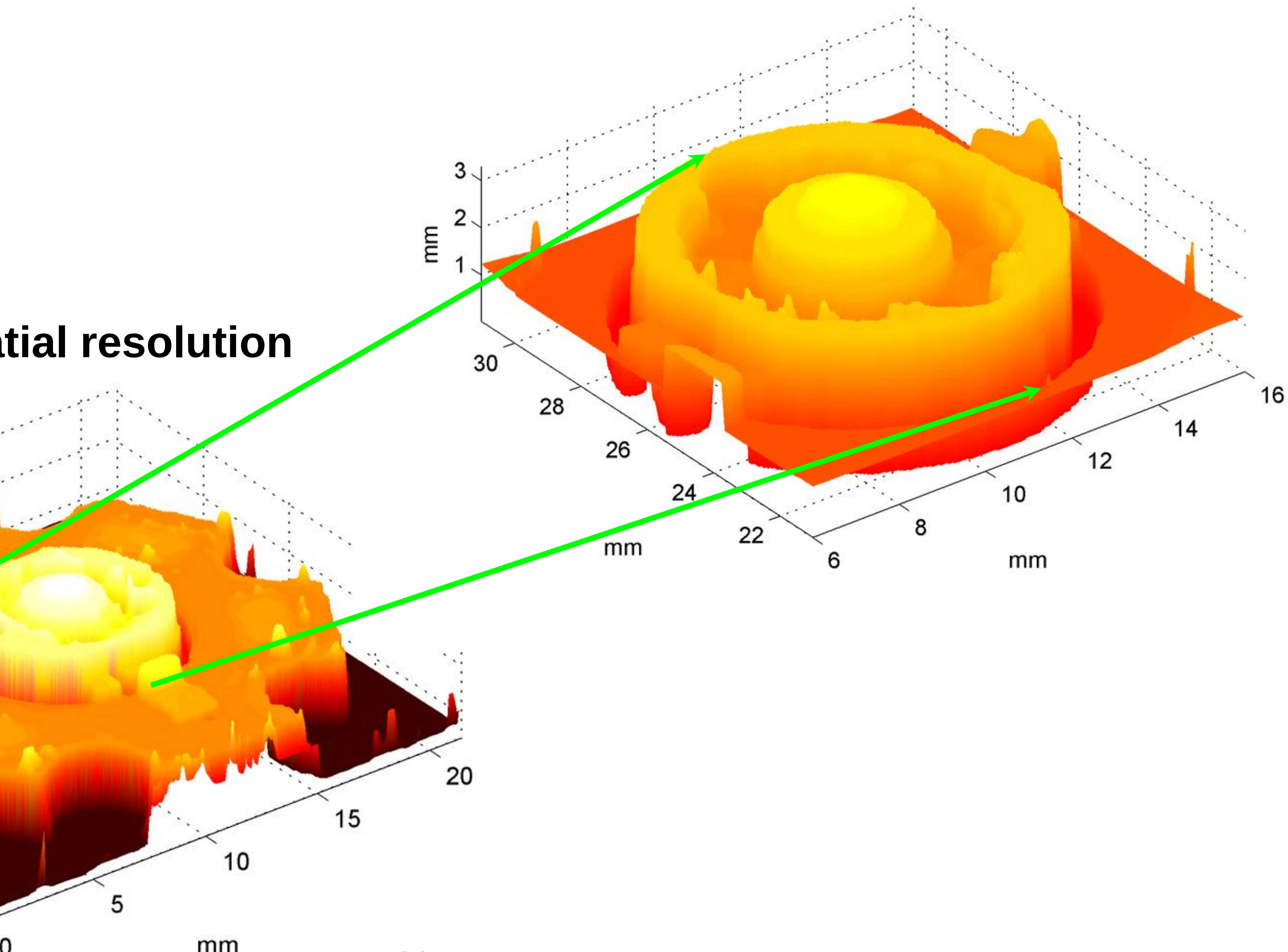
50 µm spatial resolution



Conclusions

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- **SLCDI is a non-contact metrology solution capable of simultaneously measuring both optical thickness and surface profile.**
- **SLCDI yields results that are in agreement with traditional interferometry to within 200 nm.**
- **SLCDI can measure non-traditional shapes, such as saddle mirrors and complex surfaces.**
- **This metrology topic is no longer supported by the US Army. We are seeking new funding sources for this project.**

Backup slides

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All the math...

Lumetrics DI Overview:

The Math You Need to Know: Part 1
Autocorrelation

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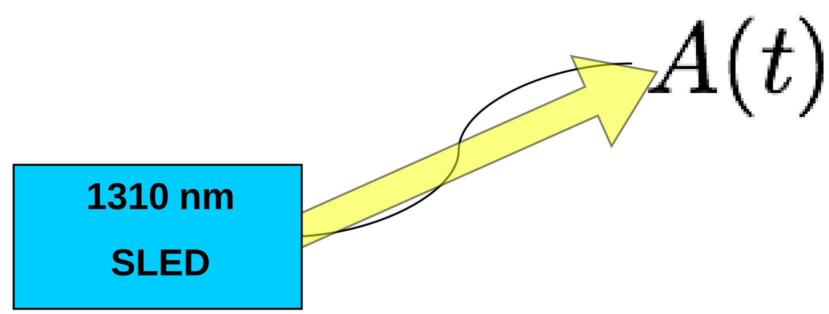
The amplitude of the electric field of the SLED light at a time t is A(t).



The autocorrelation of the field amplitude is the integral of two signals displaced by an increment of time.

$$\Gamma(t,\tau) = < A^*(t)A(t+\tau) > = \frac{\int_{-T/2}^{+T/2} A^*(t)A(t+\tau)}{T}$$

For a stationary random process, the autocorrelation is independent of the time, t, i.e.

$$\Gamma(t,\tau) = \Gamma(\tau)$$

Lumetrics DI Overview:

The Math You Need to Know: Part 2
Wiener-Khintchine Theorem

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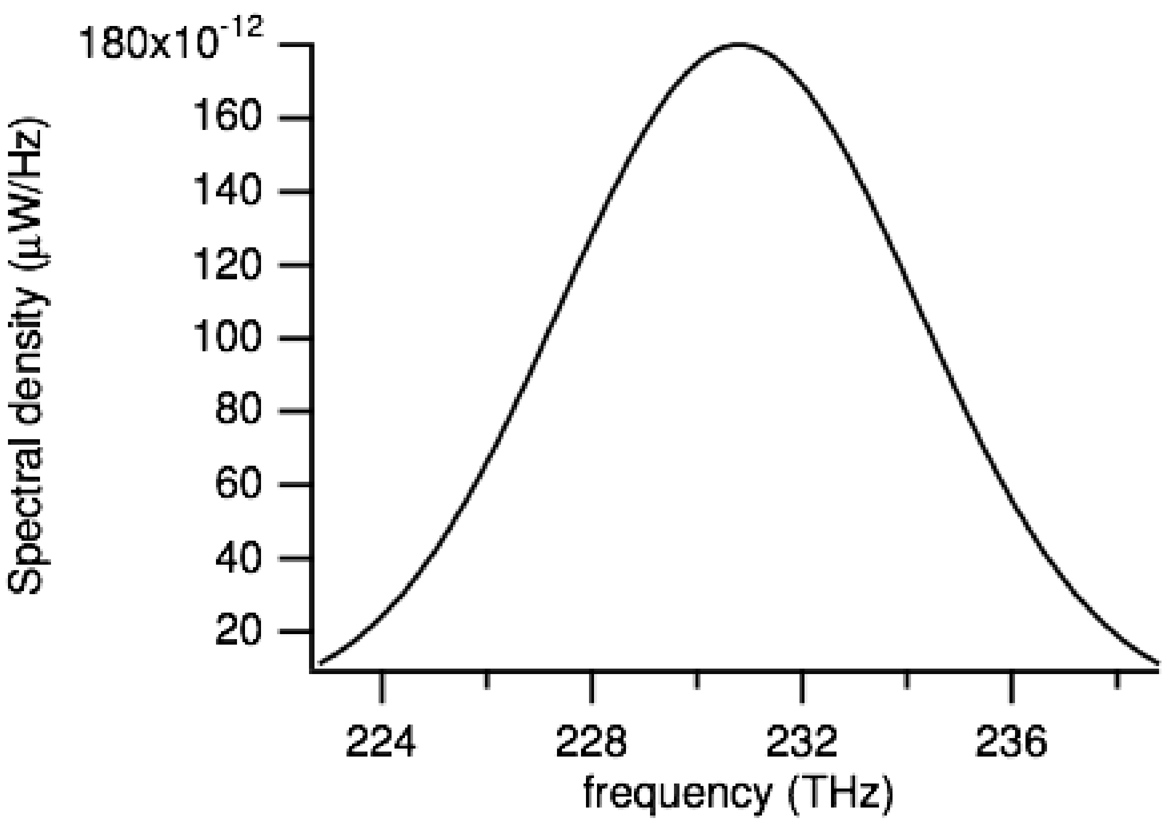
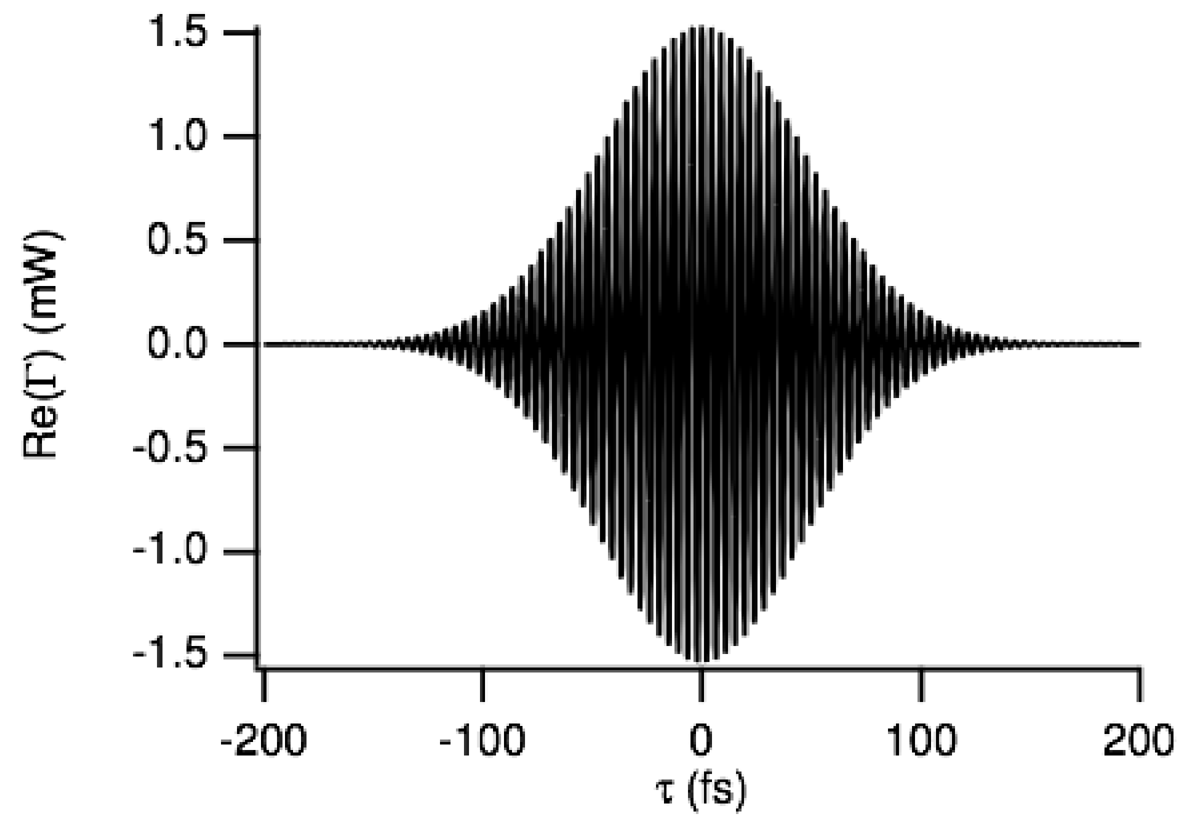
The autocorrelation is the Fourier transform of the SLED spectrum

Spectrum



Autocorrelation



$$\Gamma(\tau) = \int_{-\infty}^{+\infty} S(\nu)\exp(-i\,2\pi\nu\tau)\,d\nu.$$

$$S(\nu) = a_0 \exp\left[-4\ln(2)\left(\frac{\nu-\nu_0}{\Delta\nu}\right)^2\right]$$

$$\Gamma(\tau) = a_0\left|\frac{\Delta\nu}{2}\sqrt{\frac{\pi}{\ln(2)}}\right| \exp\left[-\left(\frac{\pi\,\Delta\nu}{2\sqrt{\ln(2)}}\tau\right)^2\right]\exp(-i2\pi\,\nu_0\,\tau).$$

$$S(\nu) = \int_{-\infty}^{+\infty} \Gamma(\tau)\exp(+i2\pi\nu\tau)\,d\tau$$

Lumetrics DI Overview:

Theory of Operation: Field Propagation, Pt. 1

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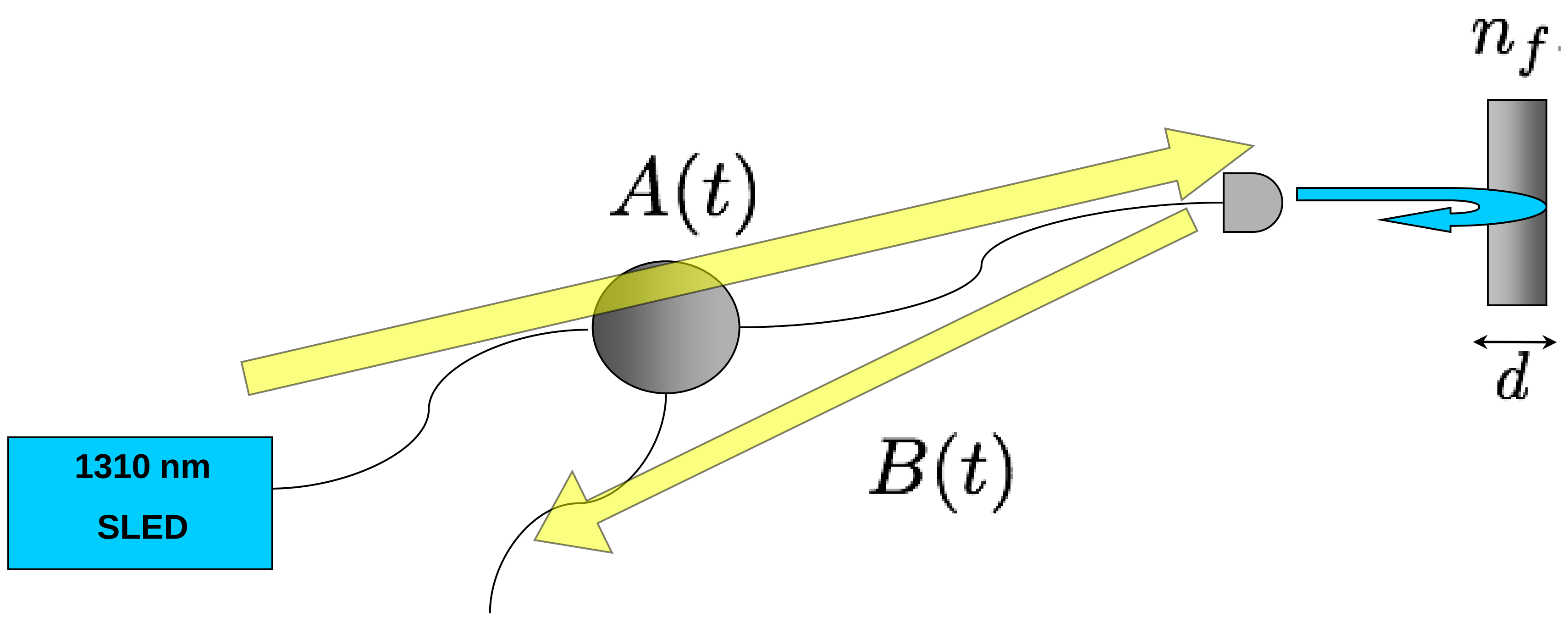
The light collected by the probe is the sum of the fields reflected from each surface.



$$B(t) = r_1\, A(t) + r_2\, A(t - 2n_f\, d/c)$$

Theory of Operation: Field Propagation, Pt. 2

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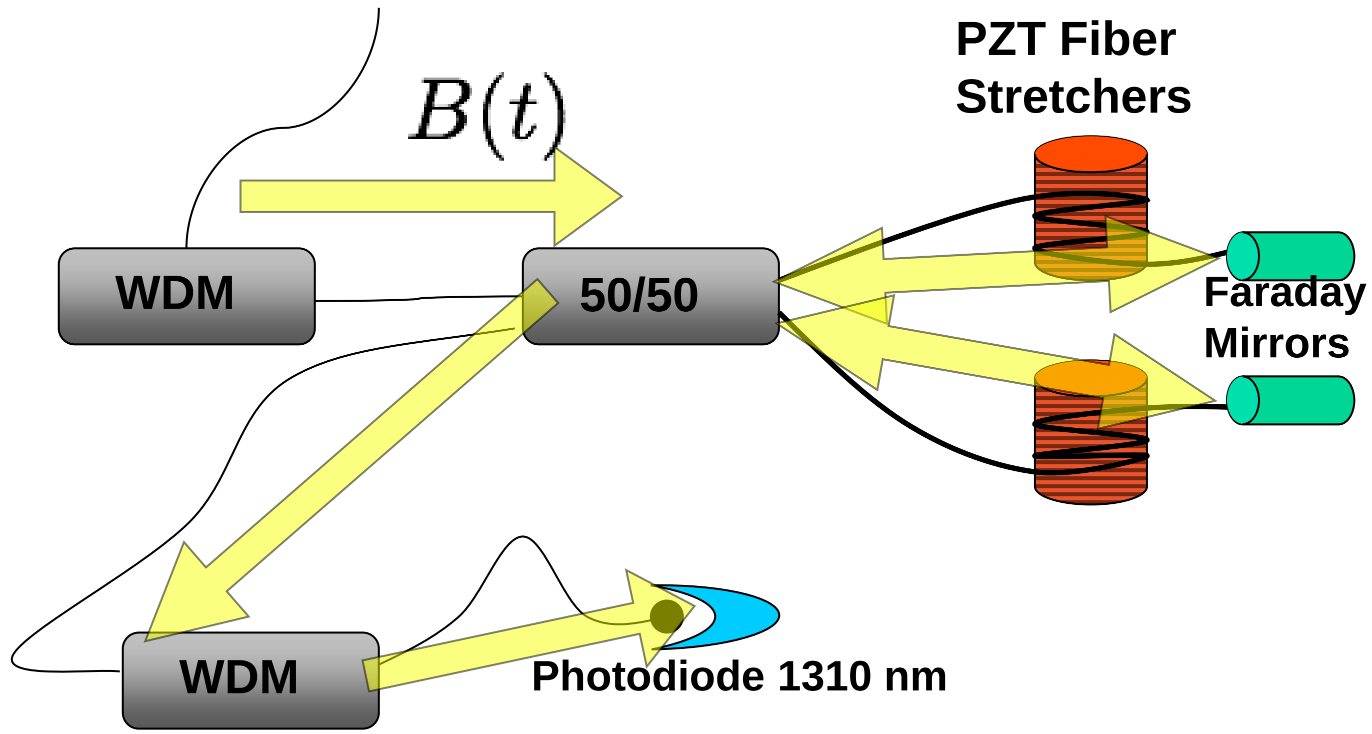
The light enters the fiber Michelson interferometer, and each returns a reflection displaced in time. The photodiode reads the intensity of the light.



$$
\begin{aligned}
I(d_1, d_2) &= \left\langle \left| B(t + 2n_i\, d_1/c) + B(t + 2n_i\, d_2/c) \right|^2 \right\rangle \\
&= \langle [B^*(t + 2n_i\, d_1/c) + B^*(t + 2n_i\, d_2/c)]\, [B(t + 2n_i\, d_1/c) + B(t + 2n_i\, d_2/c)] \rangle \\
&= \langle B^*(t + 2n_i\, d_1/c) B(t + 2n_i\, d_1/c) \rangle \cdots \\
&\quad \cdots + \langle B^*(t + 2n_i\, d_1/c) B(t + 2n_i\, d_2/c) \rangle \cdots \\
&\quad \cdots + \langle B^*(t + 2n_i\, d_2/c) B(t + 2n_i\, d_1/c) \rangle \cdots \\
&\quad \cdots + \langle B^*(t + 2n_i\, d_2/c) B(t + 2n_i\, d_2/c) \rangle \,.
\end{aligned}
$$

Lumetrics DI Overview:

Theory of operation: The Meaning, Pt. 1

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The intensity expression becomes suprisingly simple when the B terms are expanded in terms of A, and then written as autocorrelations.

peak at 0

$$
\begin{aligned}
I(\tau) &= 4\,\mathrm{Re}[r_1^* \, r_2 \, \Gamma(-2n_f \, d/c)] \cdots \\
&\cdots + 2(|r_1|^2 + |r_2|^2)\{\Gamma(0) + Re[\Gamma(\tau)]\} \cdots \\
&\cdots + 2\,\mathrm{Re}[r_1^* \, r_2 \, \Gamma(\tau - 2n_f \, d/c)] \cdots \\
&\cdots + 2\,\mathrm{Re}[r_1 \, r_2^* \, \Gamma(\tau + 2n_f \, d/c)].
\end{aligned}
$$

small constant terms

peak at $+2n_f d/c$

where $\tau = 2(d_2 - d_1)n_i/c,$

peak at $-2n_f d/c$

Theory of operation: The Meaning, Pt. 2

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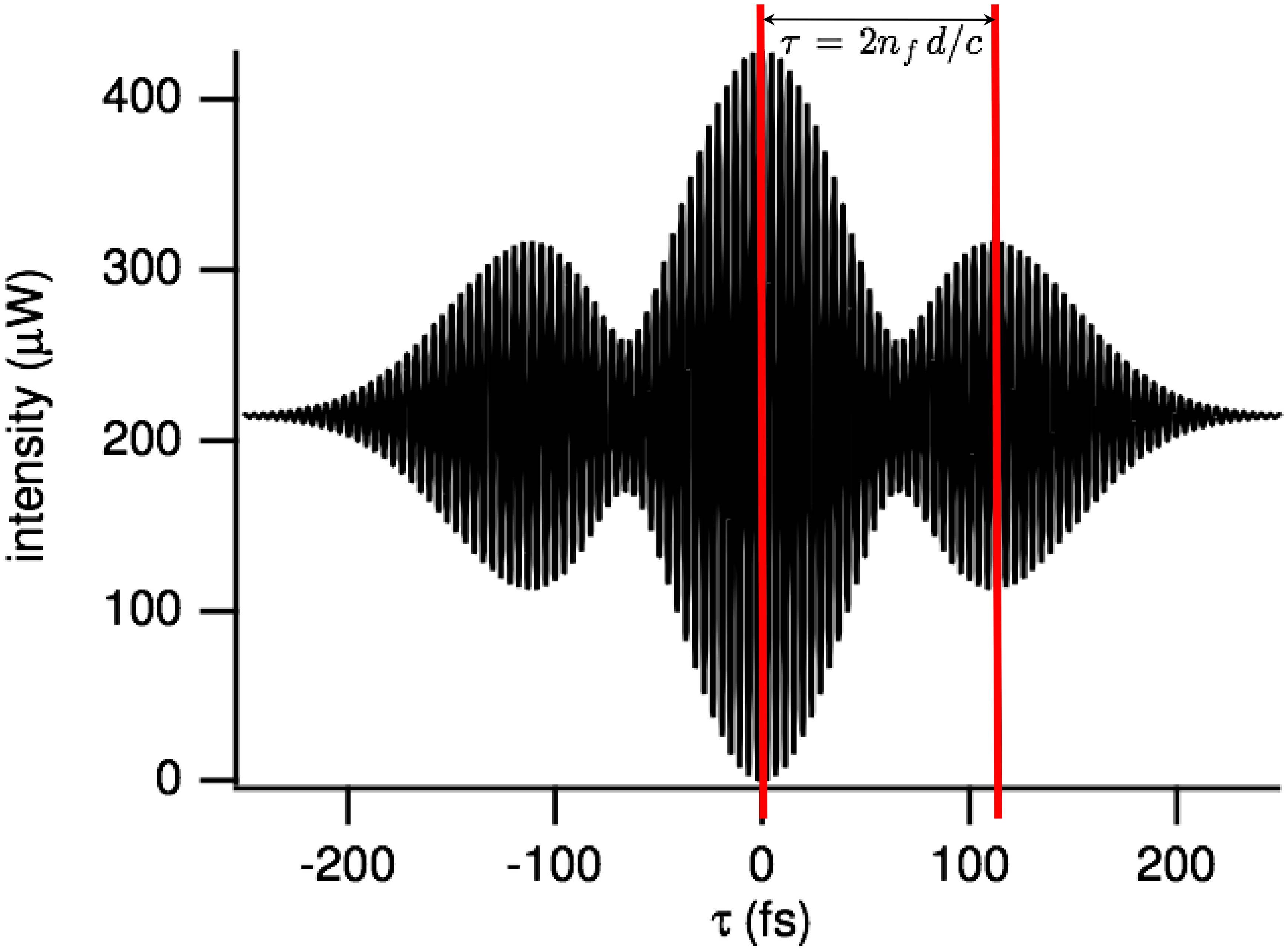
The distance from the side peak to the center peak is proportional to the optical thickness of the sample.



Scanner Overview:

The scanning software was created in LabVIEW.

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