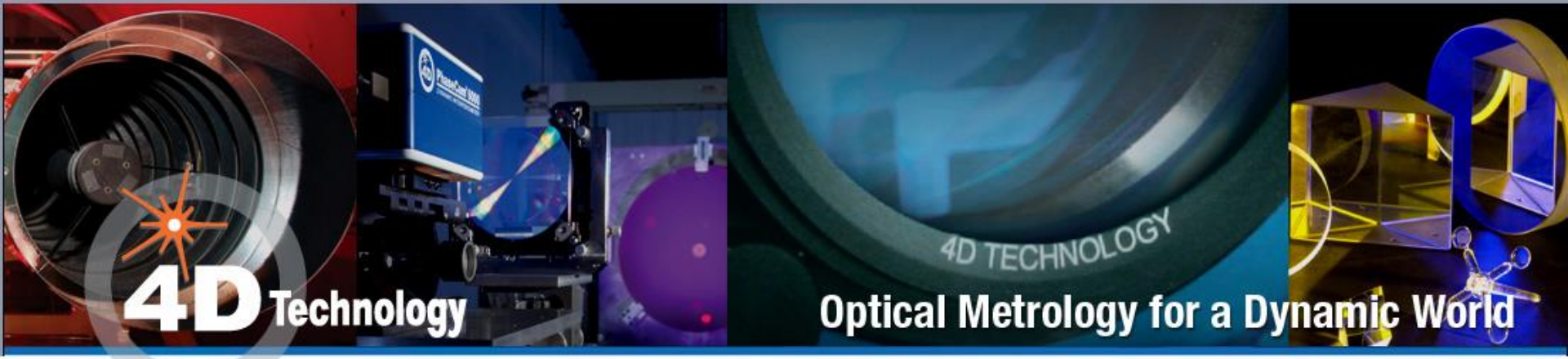


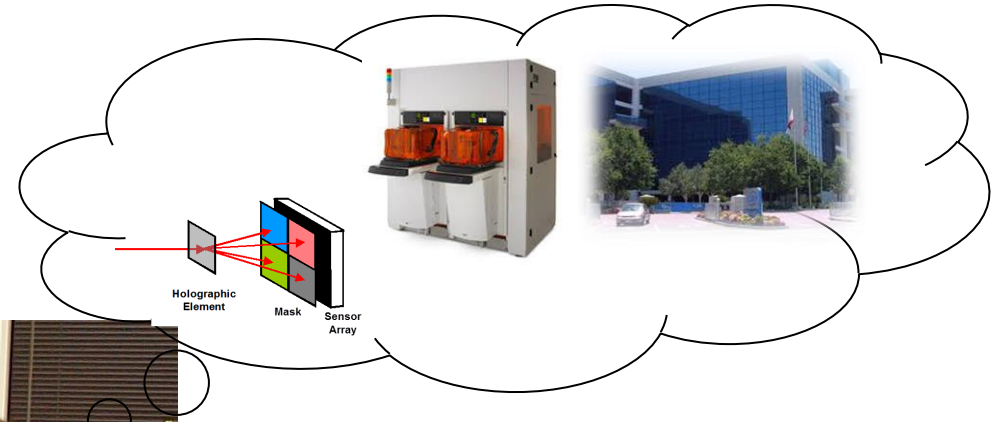
Growing a NASA Sponsored Metrology Project to Serve Many Applications and Industries

James Millerd
President, 4D Technology

Outline

- In the Beginning…
  - Early Technology
- The NASA Connection
  - NASA Programs
  - First success at NASA
  - Technology Evolution
- Where We Are Today…
  - New Applications and Industries

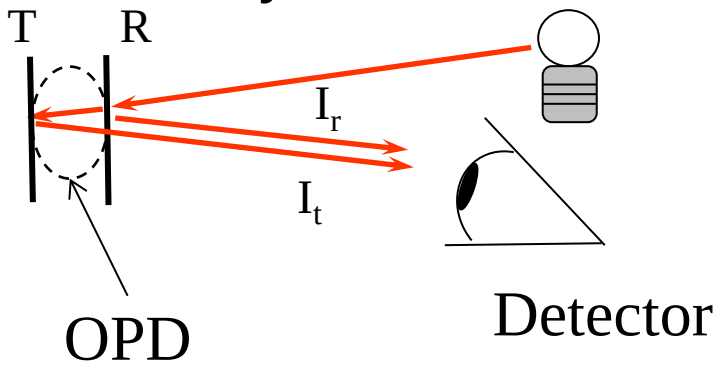
- In the beginning…



Optical Interferometry

- Measure interference between optical beams traveling two different paths

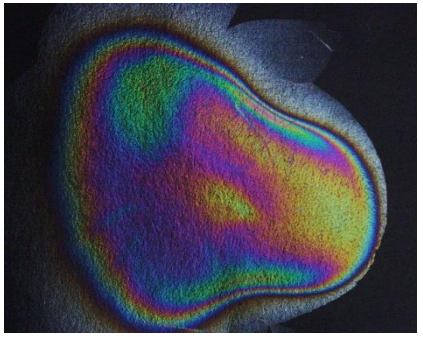
- Fizeau Cavity



Optical path difference

Function of time, position, wavelength…

$$I \sim \cos(2\pi/\lambda * \mathrm{OPD})$$



- Thin Film Interference

- White Light Interference in a Bubble

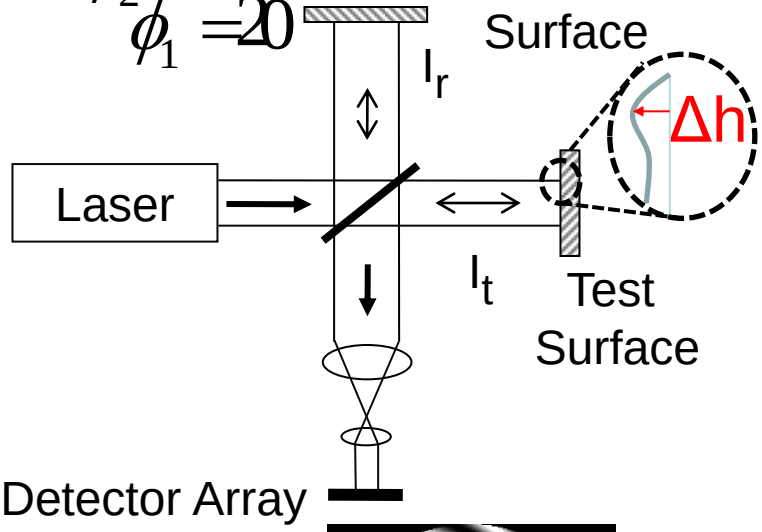
Temporal Phase-Shift Interferometry

$\phi_4 = 3\pi/2$

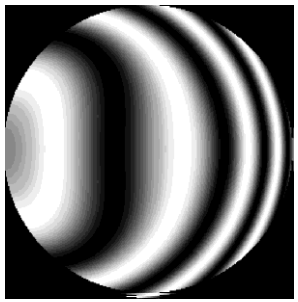
$\phi_3 = \pi$

$\phi_2 = \pi/2$

$\phi_1 = 0$



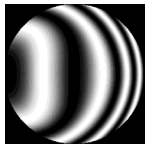
$I_2(x,y)$



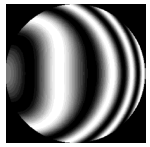
$I_n = I_T(1+\gamma COS(\phi + \phi_n)$

$\phi = 4\pi\ \Delta h/\lambda$

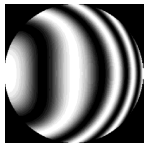
$\gamma = 2\ \sqrt{(It \bullet Ir)/(It+Ir)}$



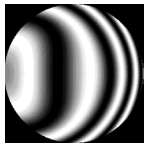
$I_1 = I_T(1+\gamma Cos(\phi))$



$I_2 = I_T(1-\gamma Sin(\phi))$



$I_3 = I_T(1-\gamma Cos(\phi))$



$I_4 = I_T(1+\gamma Sin(\phi))$

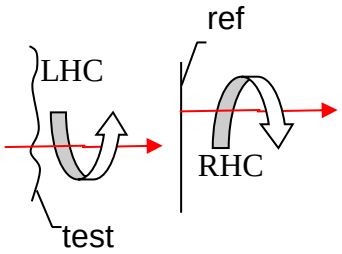
120 milliseconds for acquisition

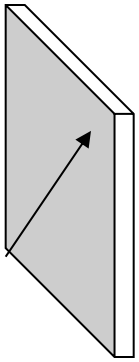
$$Tan(\phi(x,y)) = \frac{I_4(x,y) - I_2(x,y)}{I_3(x,y) - I_1(x,y)}$$

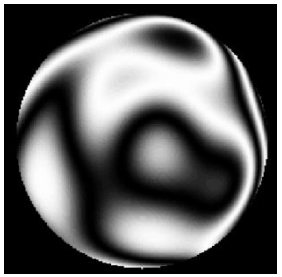
$$Height(x,y) = \frac{\lambda}{4\pi}\phi(x,y)$$

Polarization Phase Shift Method

Use polarizer as phase shifter







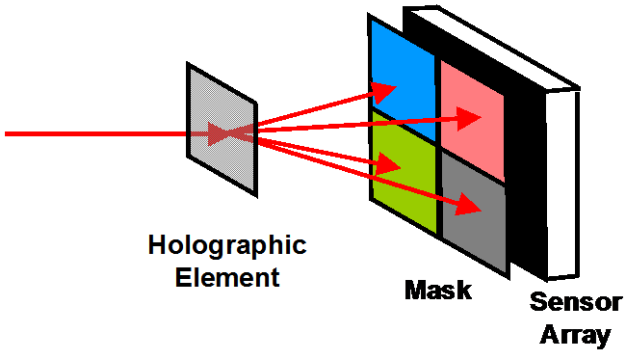
Circular polarized beams (θ) + linear polarizer (α) ⟹ $I = I_T(1+\gamma Cos\,(\theta + 2\alpha))$

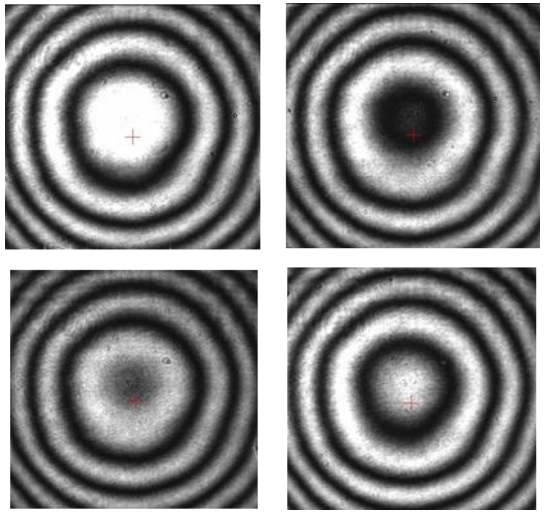
Phase-shift depends on polarizer angle

Kothiyal and Delsile, (1985)

Early Technology

Image division + bulk polarization elements



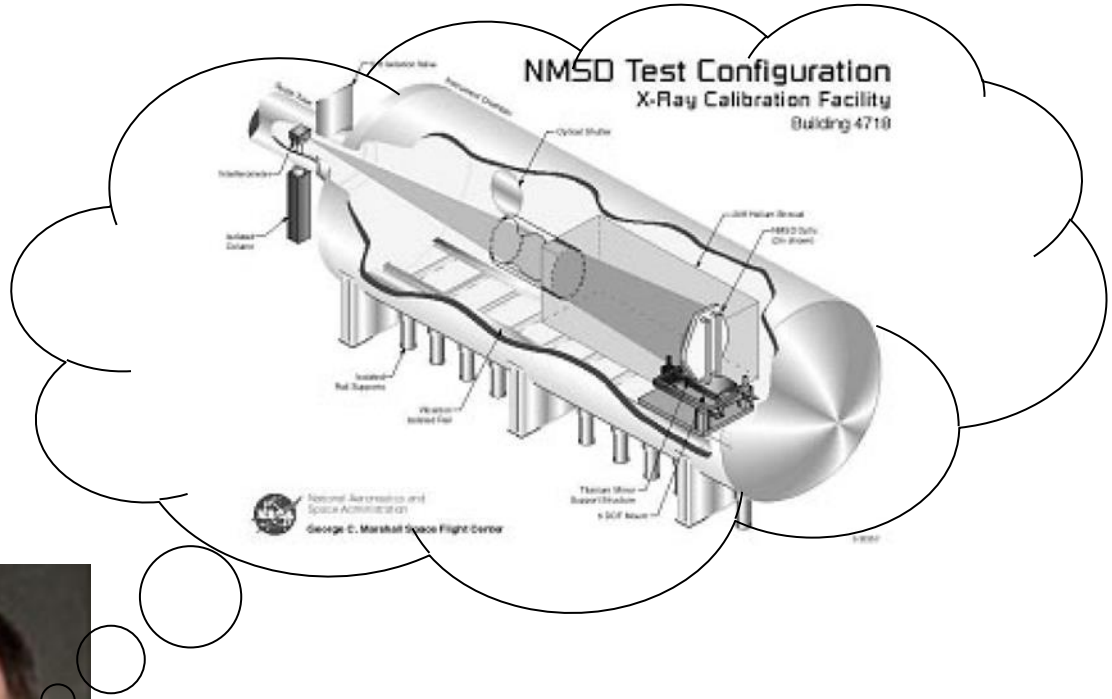


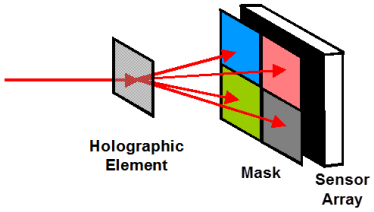
- Single Frame Acquisition
- Simplified Optical Setup

- The NASA Connection

The NASA Connection

- Then we met Phil…





+

NASA Related Projects

• 2001

PhaseCam

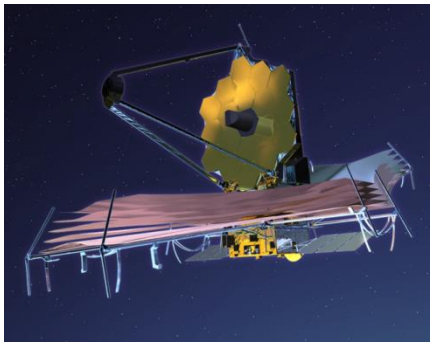
Mirror Vibration testing

Modal Analysis

• 2003

Segment cryo-figure

4Mpix + Zoom



•NASA, ITT, Ball, Tinsley…

Segment phasing

Multi-wavelength

• 2006

Backplane cryo-stability

SpeckleCam

• 2004

• 2011

FizCam

Secondary

segment vibration

High-speed

1000fps

Short Coherence

cryo-test

300mm

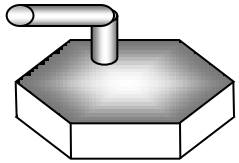
Auto-collimating

flats

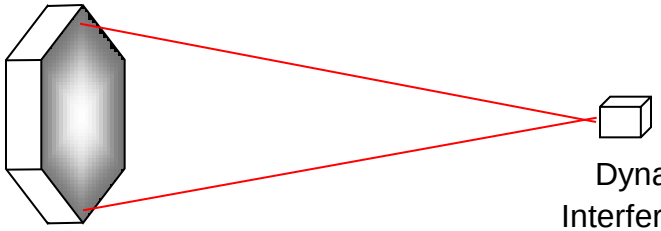
2014

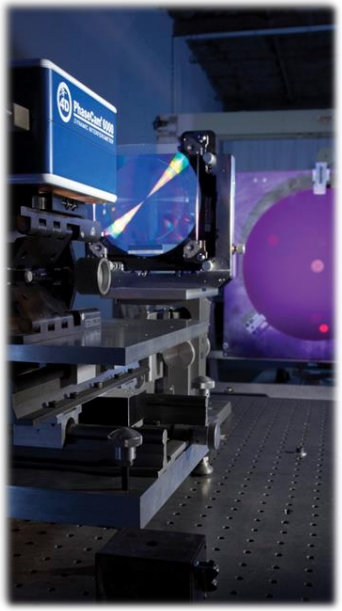
Cryo-figuring of mirror segments

- 1) Polish

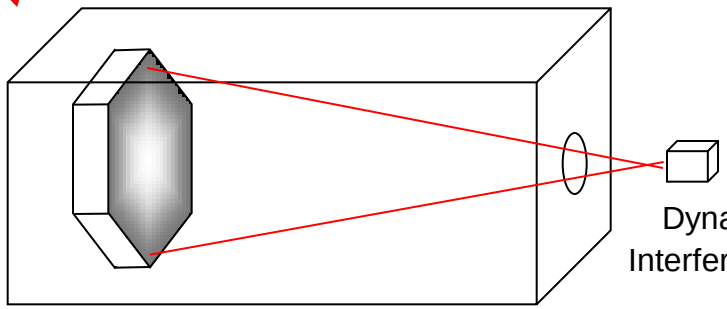


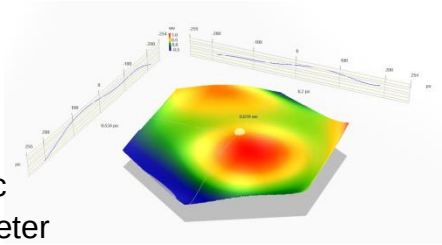
- 2) Measure at ambient





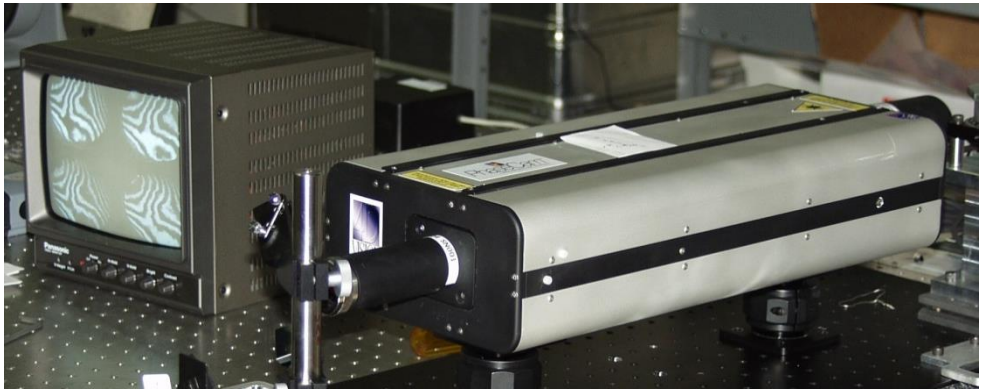
- 3) Measure at cryogenic temp





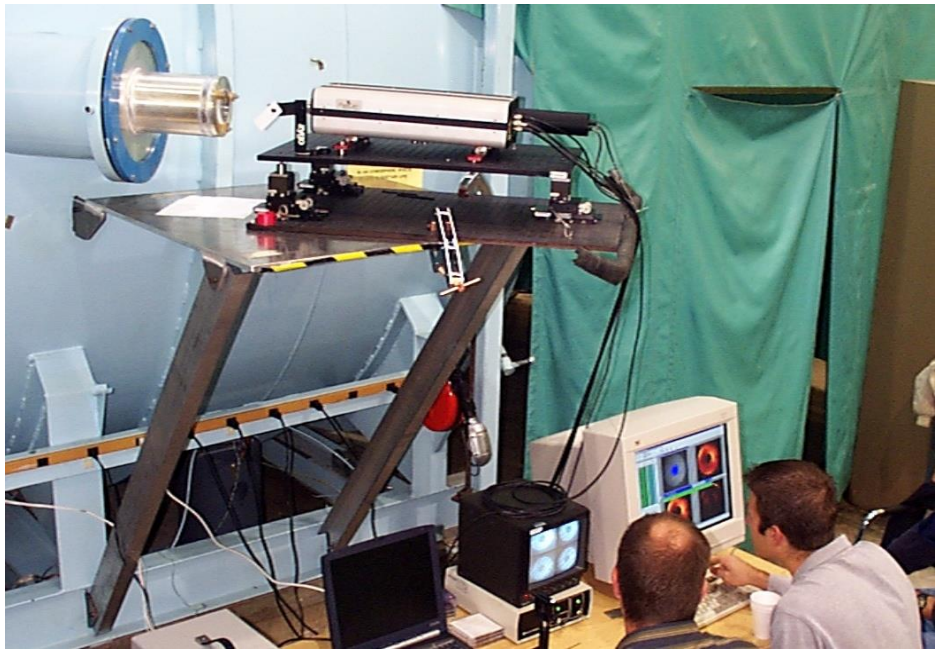
First application

- NASA Marshall - XRCF



Peak to Valley			RMS		
Uncalibrated Accuracy	Precision	Repeatability	Uncalibrated Accuracy	Precision	Repeatability
.087 wvs	.021 wvs	.0029wvs	.011 wvs	.0024 wvs	.00058 wvs
λ/11.5	λ/46	λ/348	λ/90	λ/413	λ/1711
57 nm	13.8 nm	1.8 nm	7 nm	1.5 nm	0.36 nm

Ball Aerospace – Deep Impact



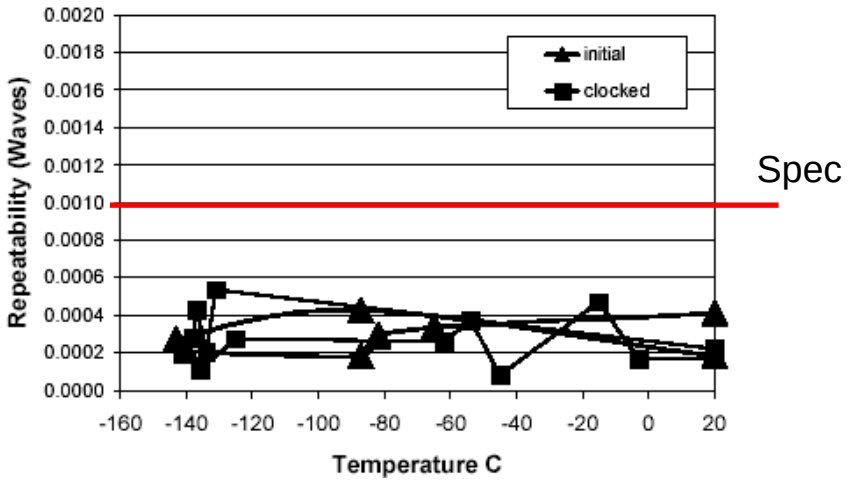
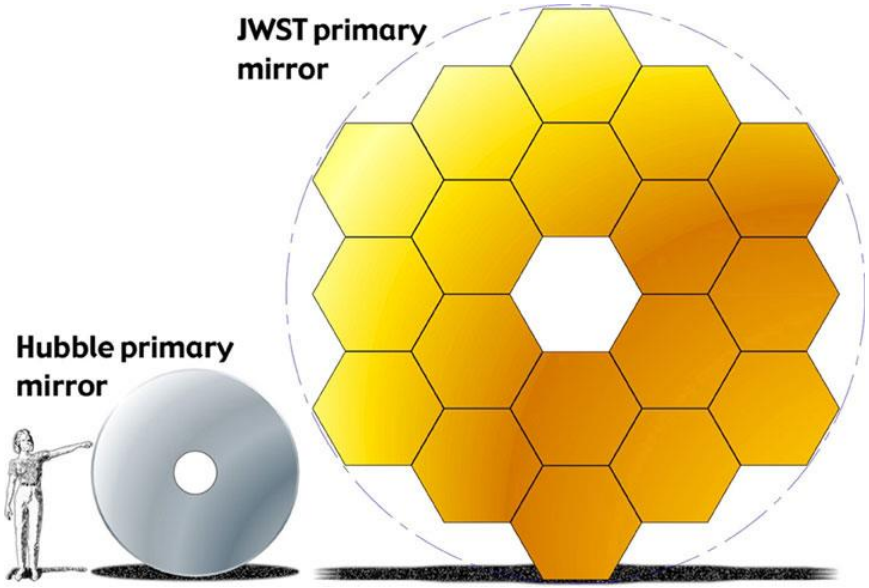
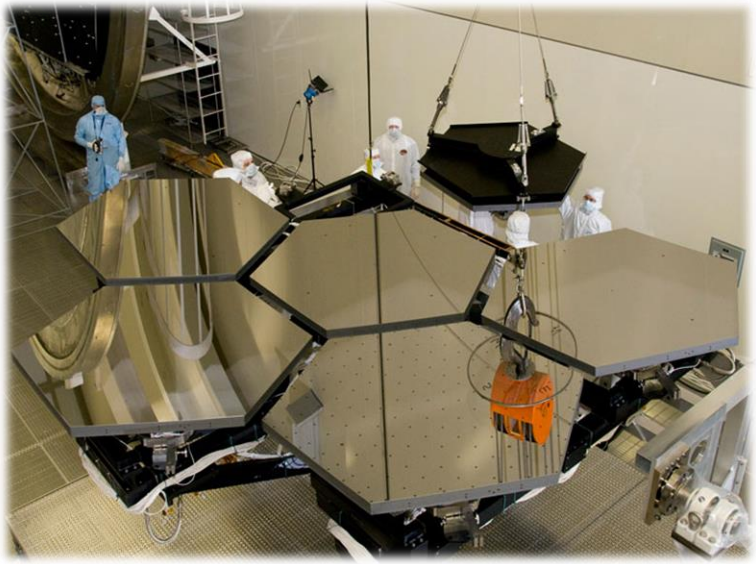


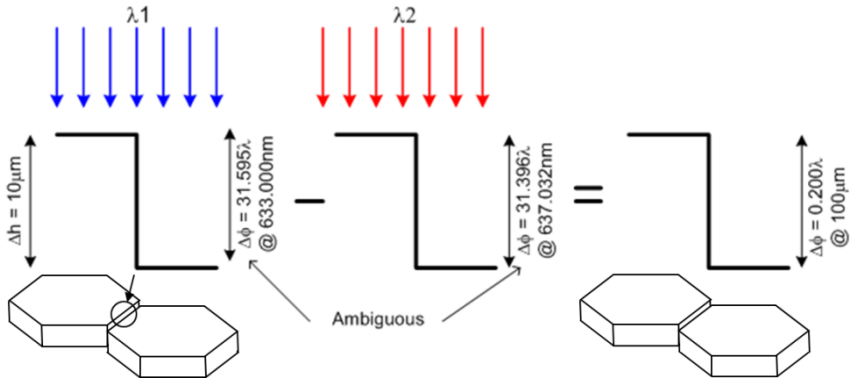
Figure testing of 300 mm Zerodur mirrors at cryogenic temperatures, Baer & Lotz, SPIE 4822-4 July 2002

Mirror Segment Discontinuity





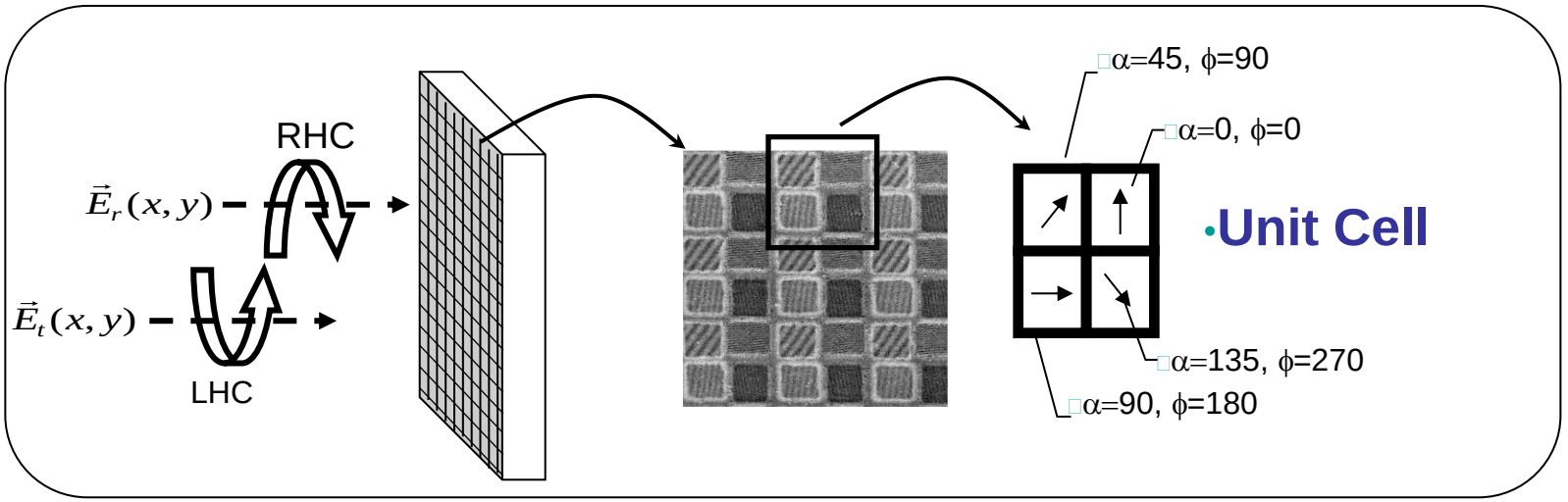
http://www.jwst.nasa.gov/



$$\lambda_s = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_2 - \lambda_1|}$$

Dynamic Phase-shift with Micropolarizer Array

- Array of oriented micropolarizers
- Similar to RGB color mask

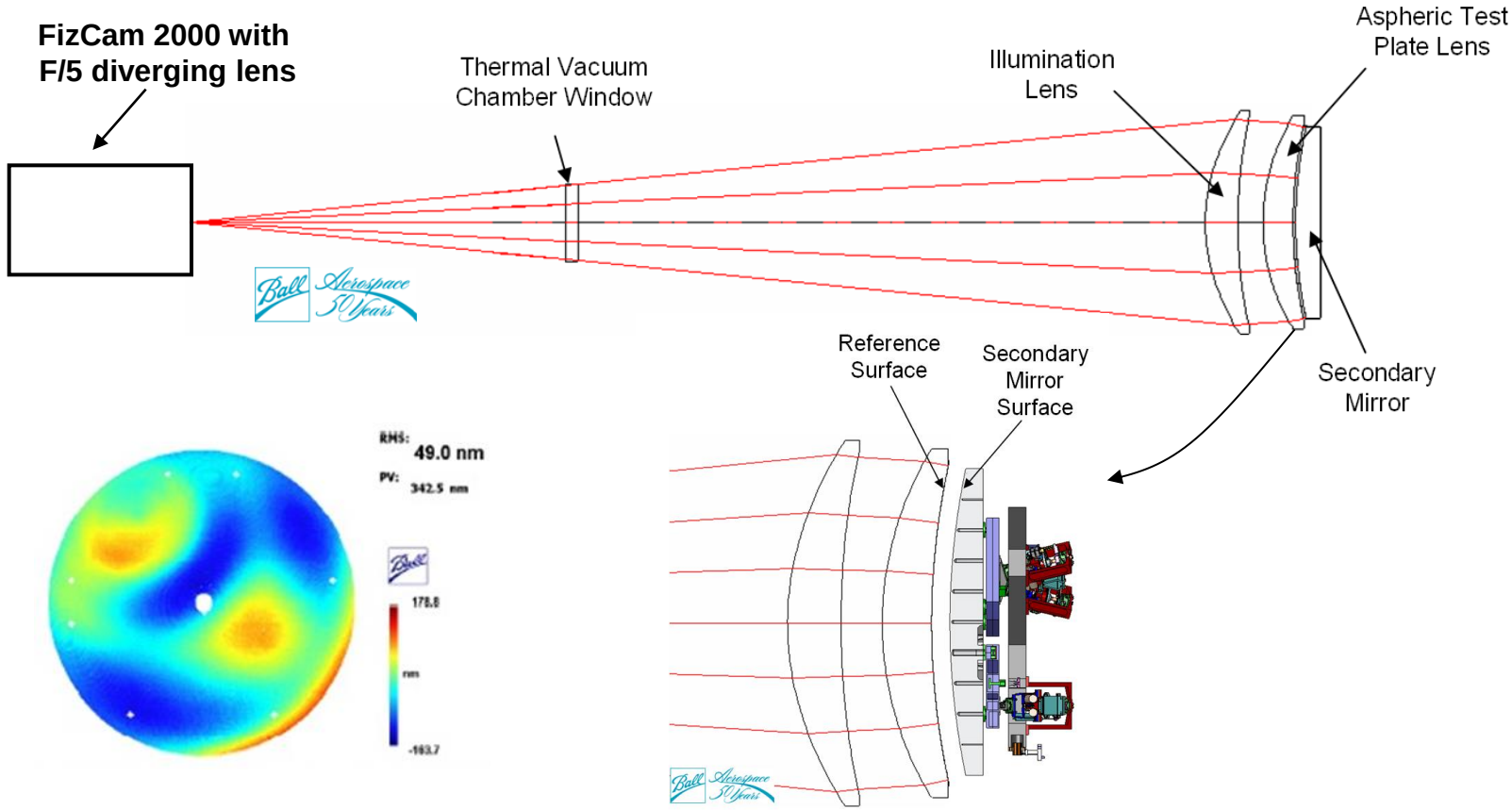


- All data is gathered in a single camera frame
- Allows common path optical arrangement (no tilted beams)
- Works with broadband source (*multi-λ, or white light*)

US Patent 7,230,719

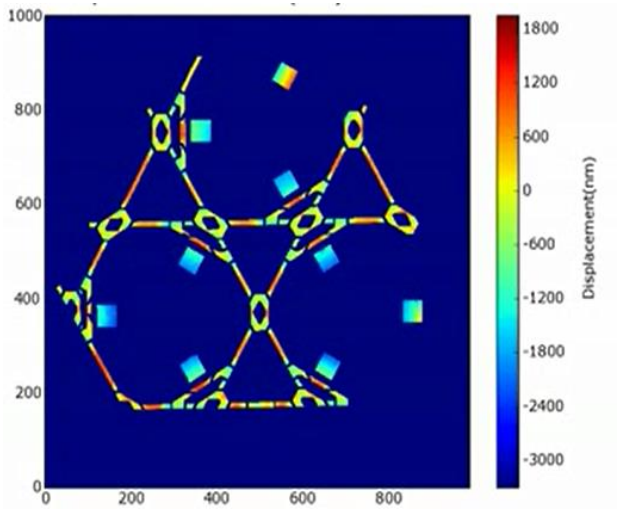
Remote Cavity Application

JWST Secondary Mirror Test Configuration
80cm diameter hyperboloid surface



"Cryogenic optical testing results of JWST aspheric test plate lens" Koby Z. Smith, Timothy C. Towell, Proc. of SPIE Vol. 8126 81260O-7

- Measurement of nm displacement of diffuse objects at 10's meters standoff



- Peter Blake, et. al., "Spatially phase-shifted digital speckle pattern interferometry (SPS-DSPI) and cryogenic structures: recent improvements", Proceedings of SPIE Vol. 7063 2008

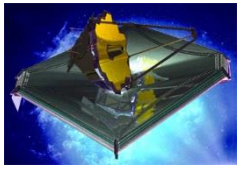
Other Applications and Industries

4D Technology

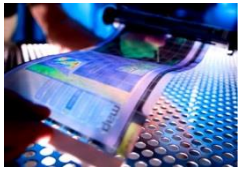
2014 - 40 employees

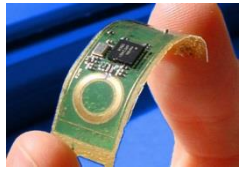
4D instruments measure surface, wavefront, and polarization, enabling our customers to:

- **Build next generation optical instruments**
  - Space-based optical systems
  - Large astronomical telescopes

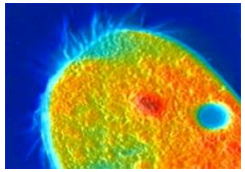




- **Improve manufacturing of industrial and consumer products**
  - Semiconductors, displays, data storage
  - Flexible electronics





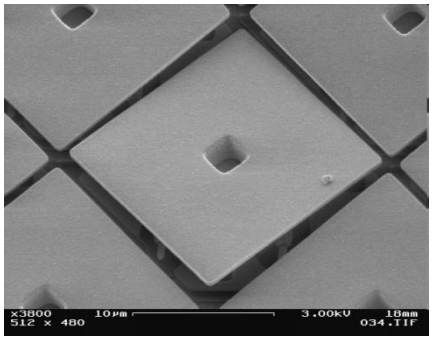
- **Increase fundamental understanding**
  - Bio-medical research
  - Astronomy

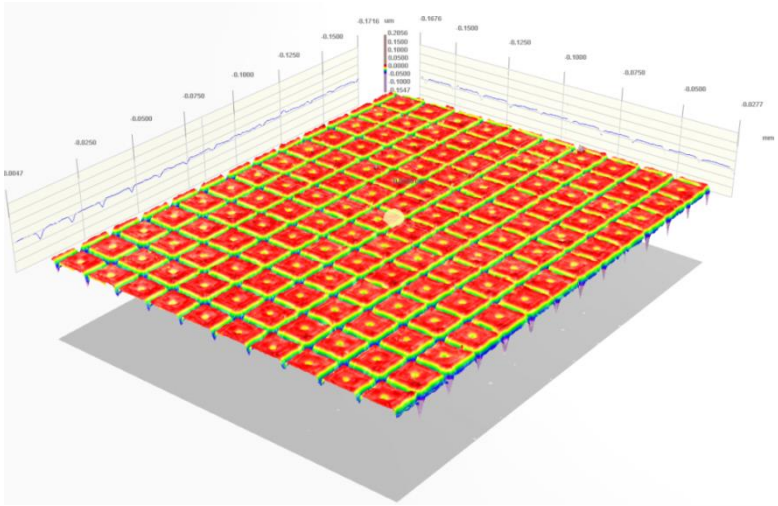


- International Sales, Service and Support

Semiconductor and MEMS

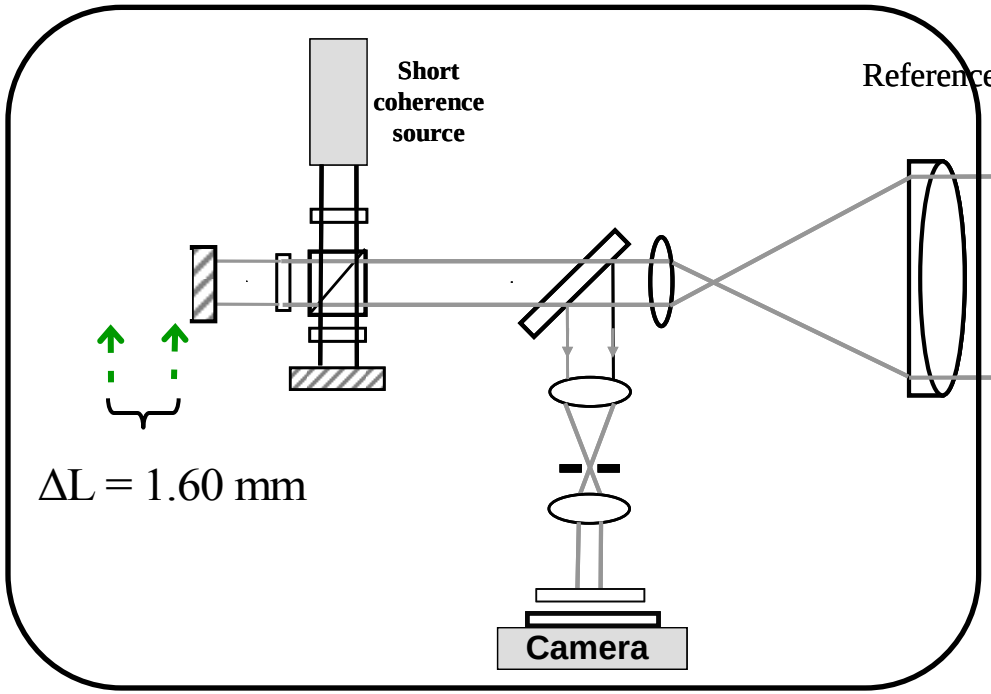
- 193nm
- Photolithography
  - Wafer chucks



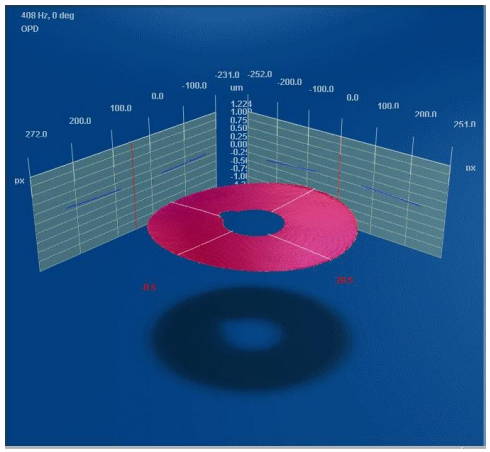


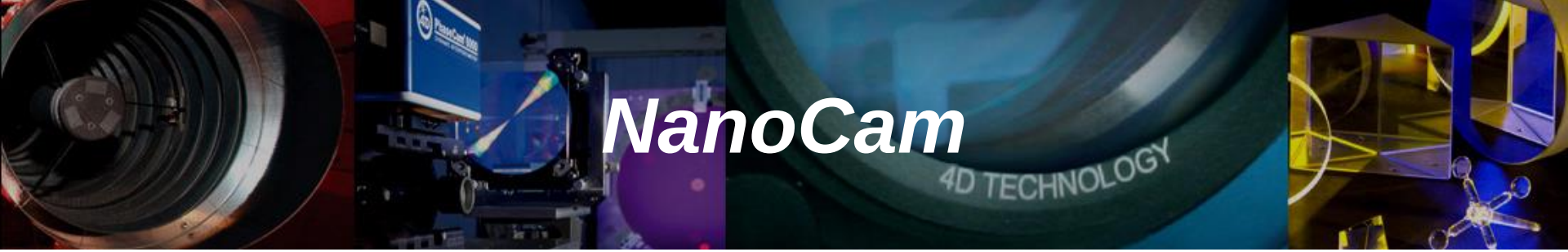
- Digital micro-mirror device

FizCam – Data Storage



- Disk drive excited at 400Hz





NanoCam

- 3D - Optical surface roughness – critical for large optics
- Micro-scope based system
- Dynamic Measurement – operation anywhere

In-situ polishing process control (On-tool)

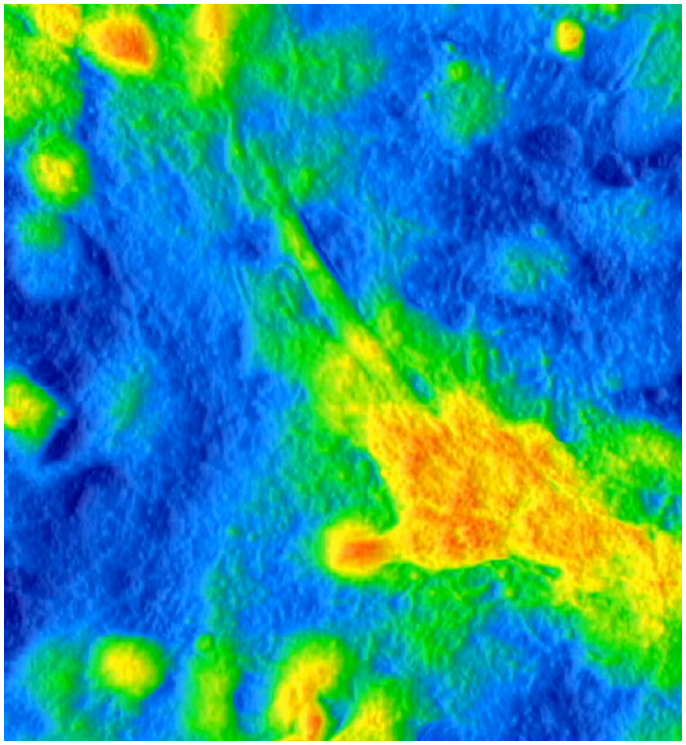
Courtesy of Zeeko Ltd

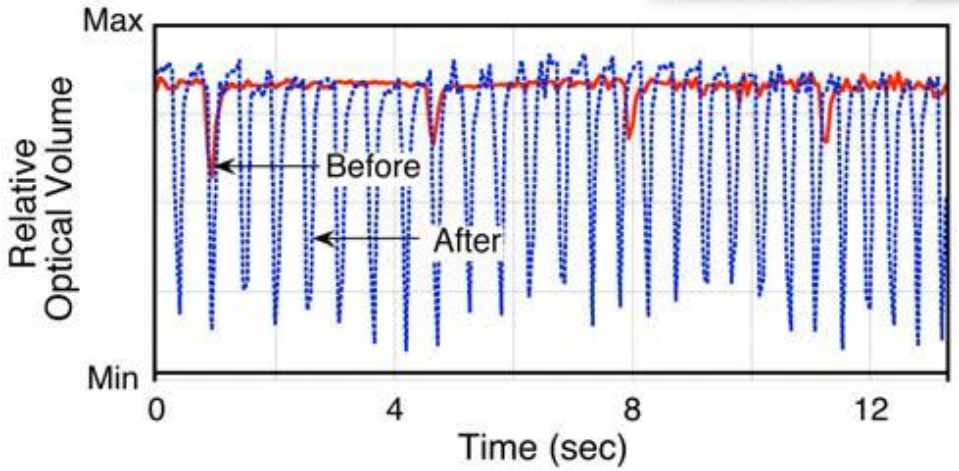
On-optic measurement

Courtesy Optical Surface Technologies

BioCam
Quantitative Biological Imaging

- Rat cardiac myocytes – before & after medication

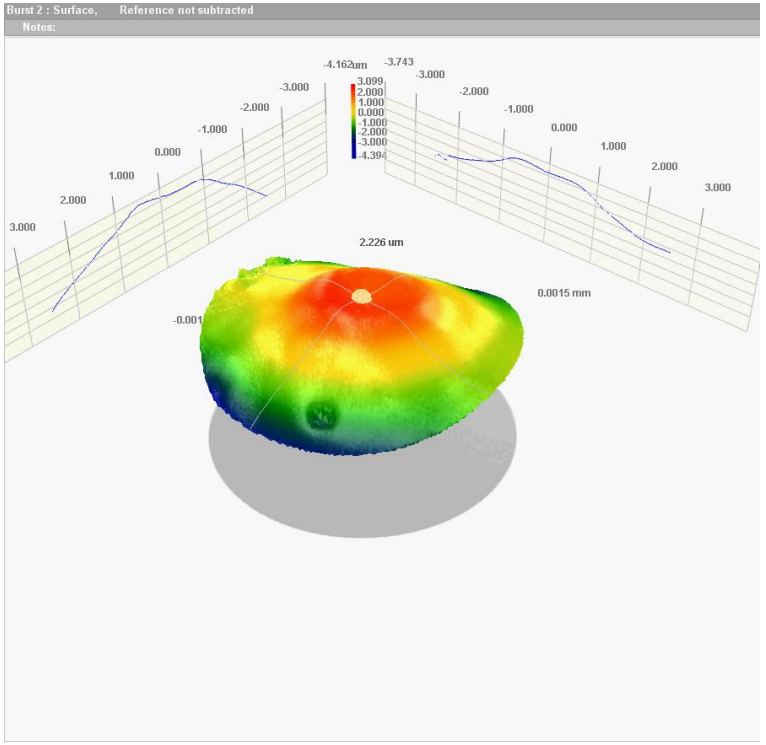


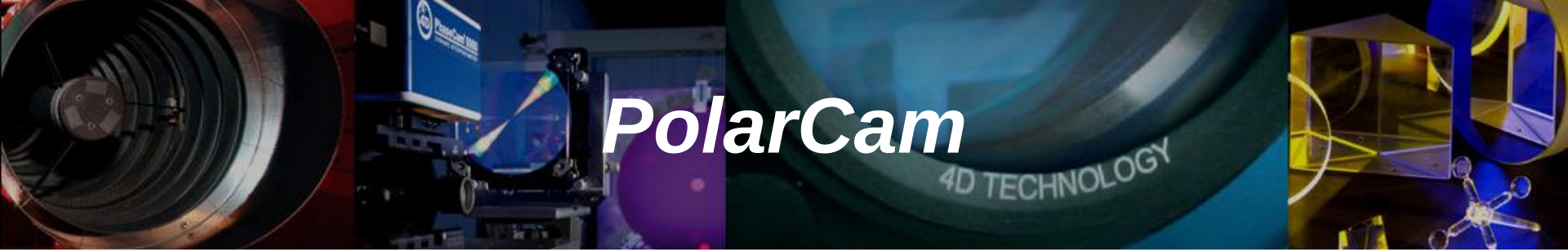


- Both frequency and strength are measured

PhaseCam - Ophthalmic

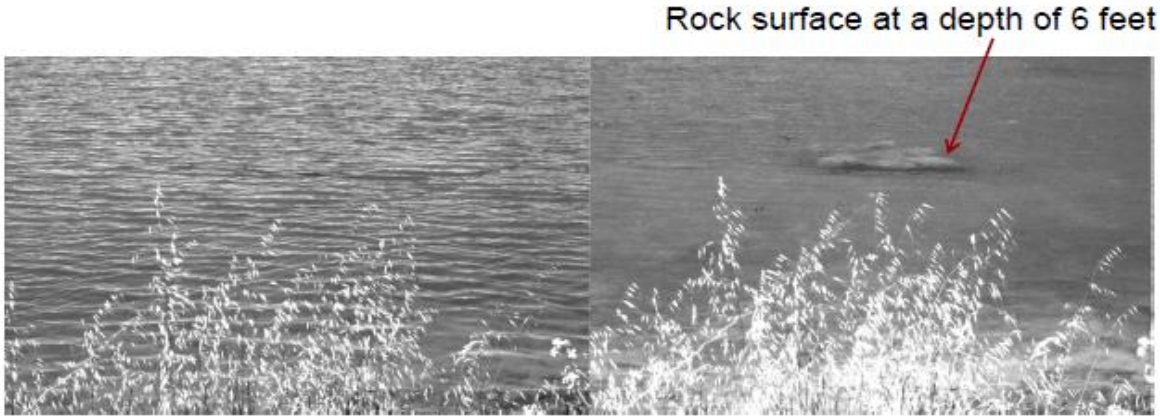
- Cornea measurement
- Tear film dynamics
- Optics





Micropolarizer Camera

- Enables whole-field, Dynamic polarimetry
  - Wide variety of wavelengths and sensor formats
- Passive illumination
  - Target discrimination, Image enhancement

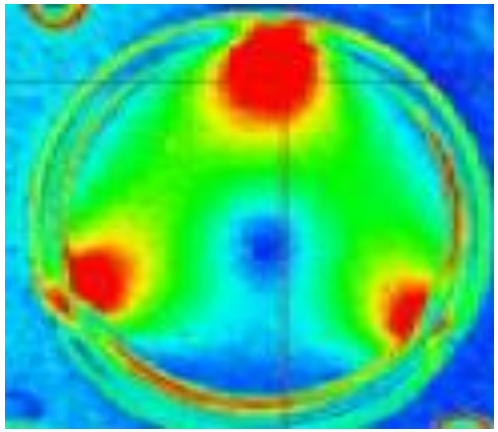


- Reference Camera
- Enhanced with DoLP

PolarCam – Active Illumination

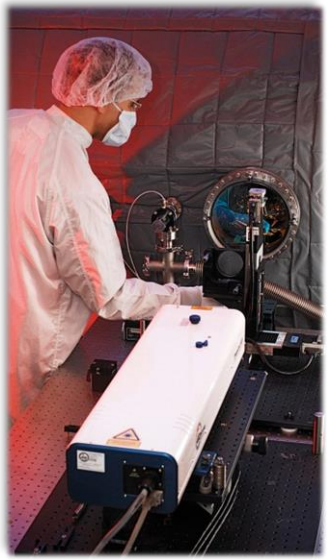
- Real-time, quantitative, independent of orientation
- Product inspection (e.g. containers, packaging, eye wear)

- **25mm diameter window: 0 – 70 nm birefringence**



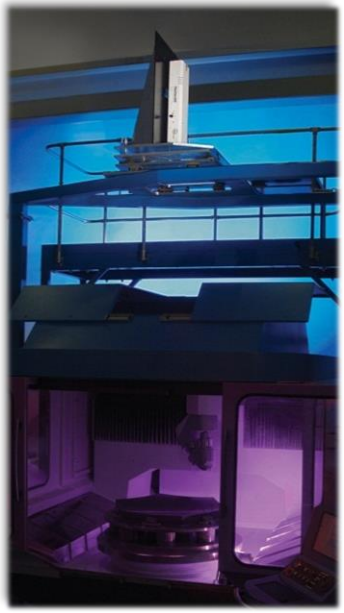
4D and NASA

- NASA sponsored development has lead to:
  - New Technology
  - Sustained Job Creation
  - Better Metrology for Telescopes
  - Industrial Process Improvement
  - Fundamental Science

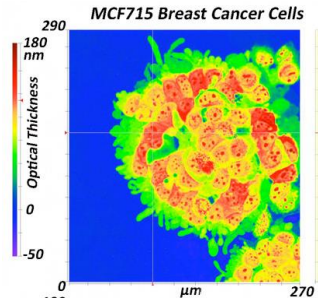


Courtesy of Ball Aerospace

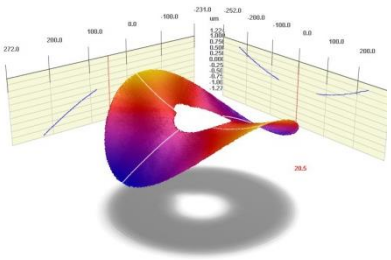
http://www.jwst.nasa.gov/



Courtesy of Zeeko Ltd.



Disk drive 400Hz



Thank you!