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

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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**
  - $T$  
  - $R$  
  - $I_r$  
  - $I_t$  
  - OPD

Optical path difference
Function of time, position, wavelength…

$I \sim \cos\left(\frac{2\pi}{\lambda \times OPD}\right)$

- **Source**
- **Detector**
- **Thin Film Interference**
- **White Light Interference in a Bubble**
Temporal Phase-Shift Interferometry

\[ \phi = 4\pi \frac{\Delta h}{\lambda} \]

\[ \gamma = 2 \sqrt{(I_t \cdot I_r)/(I_t + I_r)} \]

\[ I_n = I_T(1 + \gamma \cos(\phi + \phi_n)) \]

\[ I_1 = I_T(1 + \gamma \cos(\phi)) \]

\[ I_2 = I_T(1 - \gamma \sin(\phi)) \]

\[ I_3 = I_T(1 - \gamma \cos(\phi)) \]

\[ I_4 = I_T(1 + \gamma \sin(\phi)) \]

120 milliseconds for acquisition

\[ \tan(\phi(x, y)) = \frac{I_4(x, y) - I_2(x, y)}{I_3(x, y) - I_1(x, y)} \]

\[ \text{Height}(x, y) = \frac{\lambda}{4\pi} \phi(x, y) \]
Polarization Phase Shift Method

Use polarizer as phase shifter

Circular polarized beams ($\theta$) + linear polarizer ($\alpha$) \[ I = I_T(1+\gamma\cos(\theta + 2\alpha)) \]

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
Then we met Phil...
NASA Related Projects

- **2001** PhaseCam
  - Modal Analysis
  - 4Mpix + Zoom

- **2003** Mirror Vibration testing

- **2004** FizCam
  - Short Coherence

- **2006** Segment cryo-figure
  - Multi-wavelength
  - SpeckleCam

- **2006** Segment phasing
  - 2011 High-speed 1000fps
  - Backplane cryo-stability

- 2014
  - Auto-collimating flats
  - 300mm

- 2011
  - NASA, ITT, Ball, Tinsley…

- Segment vibration

11/19/2014
Cryo-figuring of mirror segments

- 1) Polish
- 2) Measure at ambient
- 3) Measure at cryogenic temp

Dynamic Interferometer
Thermal Chamber
Residual
• NASA Marshall - XRCF

<table>
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<tr>
<th>Peak to Valley</th>
<th>Uncalibrated Accuracy (wvw)</th>
<th>Precision (nm)</th>
<th>Repeatability (nm)</th>
<th>Uncalibrated Accuracy (wvw)</th>
<th>Precision (nm)</th>
<th>Repeatability (nm)</th>
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<tr>
<td>RMS</td>
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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-\(\lambda\), or white light)

Unit Cell

- \(\alpha=45, \phi=90\)
- \(\alpha=0, \phi=0\)
- \(\alpha=135, \phi=270\)
- \(\alpha=90, \phi=180\)
Remote Cavity Application

JWST Secondary Mirror Test Configuration
80cm diameter hyperboloid surface

FizCam 2000 with F/5 diverging lens

Thermal Vacuum Chamber Window

Illumination Lens

Aspheric Test Plate Lens

Reference Surface

Secondary Mirror Surface

Secondary Mirror

“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

Other Applications and Industries
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
ΔL = 1.60 mm

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)

On-optic measurement

Courtesy Optical Surface Technologies

Courtesy of Zeeko Ltd
• Rat cardiac myocytes – before & after medication

• Both frequency and strength are measured
- 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

Rock surface at a depth of 6 feet

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
NASA sponsored development has lead to:

- New Technology
- Sustained Job Creation
- Better Metrology for Telescopes
- Industrial Process Improvement
- Fundamental Science

Disk drive 400Hz

Courtesy of Ball Aerospace

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

Courtesy of Zeeko Ltd.
Thank you!