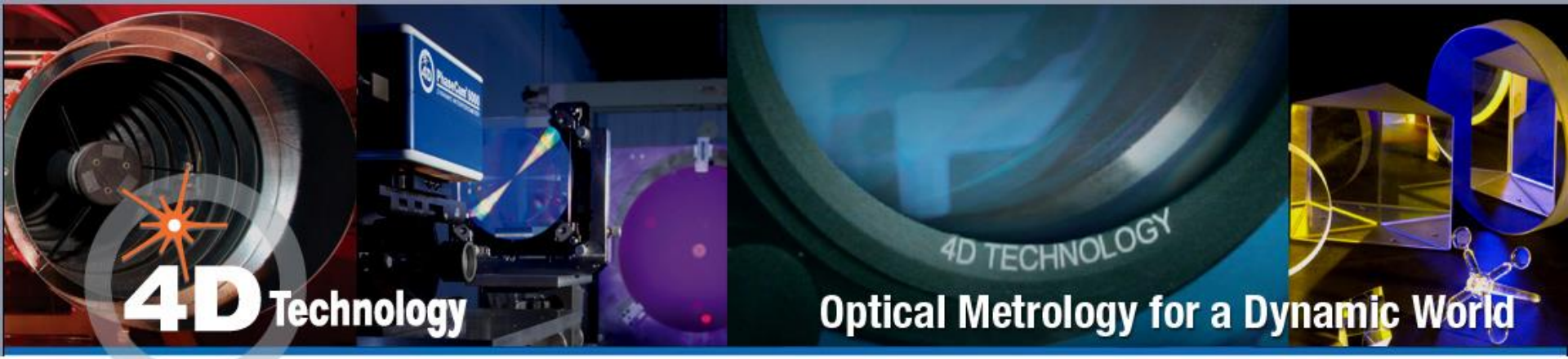
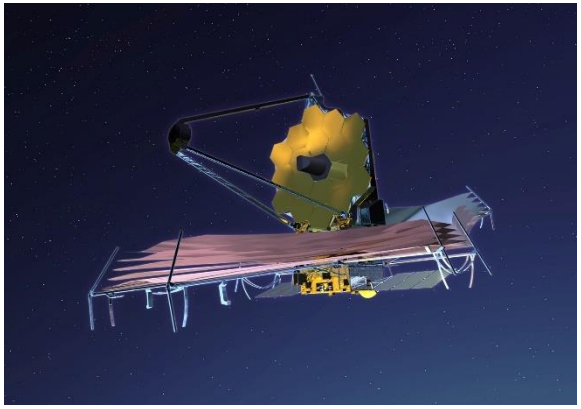


Dynamic Interferometry: Applications of High Speed Interferometry

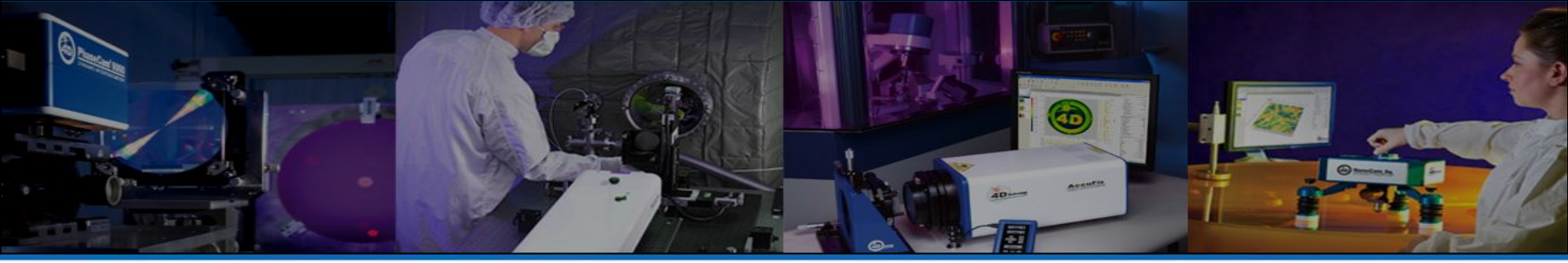
Michael North Morris
4D Technology Corporation



Mirror Tech Days 2017

Outline

- Dynamic Interferometry
- High Speed Interferometer
- JWST Testing
- Beyond JWST
  - Combine High Speed with ESPI
  - New Interferometer Status



Dynamic Interferometry

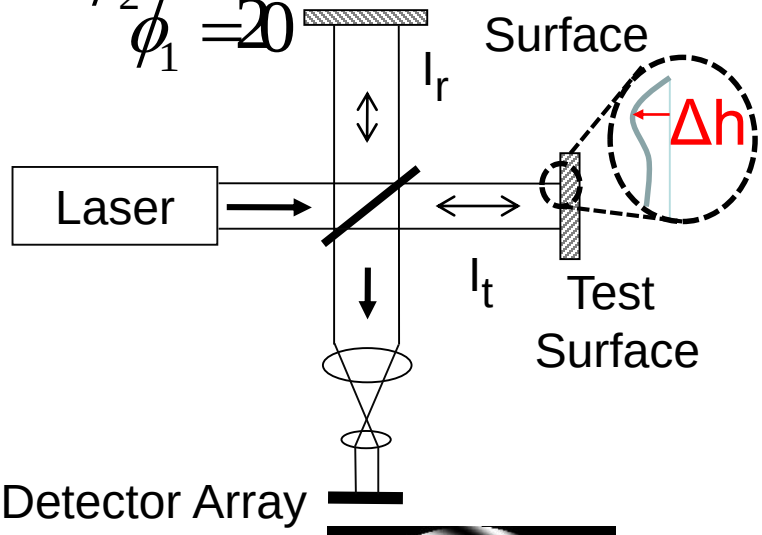
Temporal Phase-Shift Interferometry

$\phi_4 = \frac{3\pi}{2}$

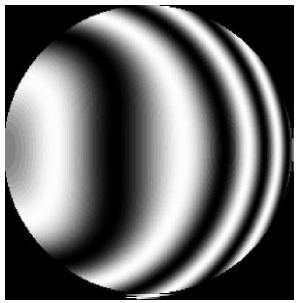
$\phi_3 = \pi$

$\phi_2 = \frac{\pi}{2}$

$\phi_1 = 0$



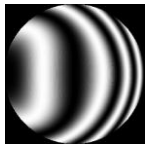
$I_2(x,y)$



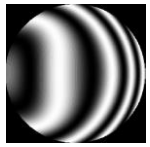
$I_n = I_T(1+\gamma COS(\phi + \phi_n)$

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

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



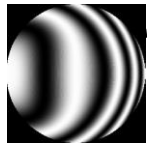
$I_1 = I_T(1+\gamma Cos(\phi))$



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

s it a hill or valley?

flectivity or surface?



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

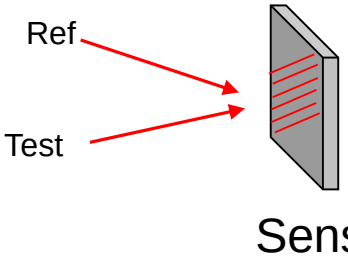
$I_4 = I_T(1+\gamma Sin(\phi))$

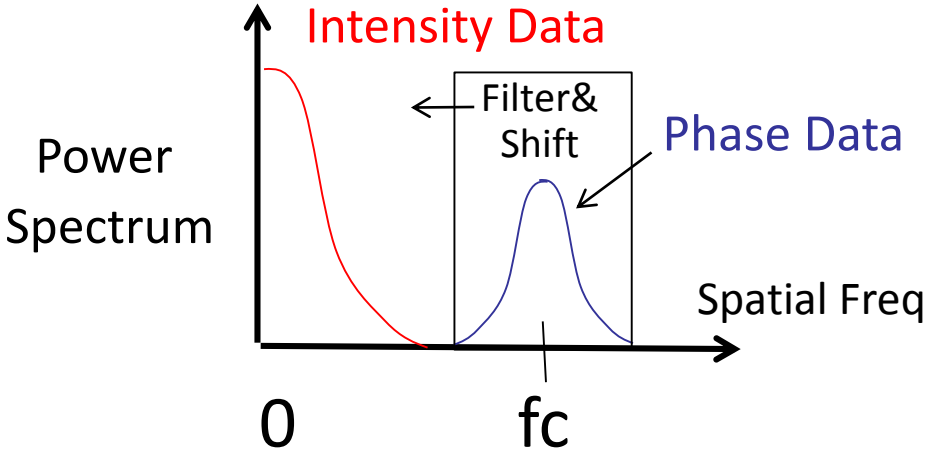
120 milliseconds for acquisition

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

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

Spatial Carrier Dynamic Sensor



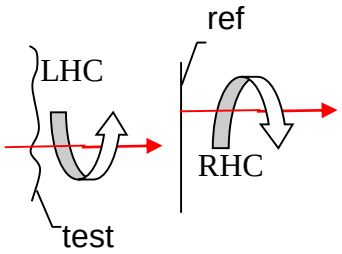


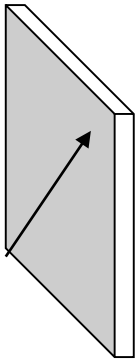
- Convenient to implement
- FT or convolution approach
- Off-axis beams – can cause retrace
  - Requires calibration
    - $\lambda/10$ flats special optics
    - Special Data Processing

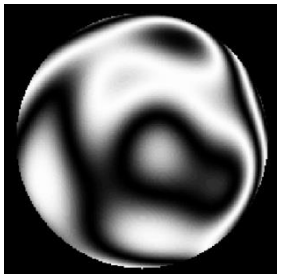
M. Kuchel, " The new Zeiss interferometer," SPIE Vol. 1332 Optical Testing and Metrology III: Recent Advances in Industrial Optical Inspection, p655-663, 1990

Polarization Phase Shift Method

Use polarizer as phase shifter





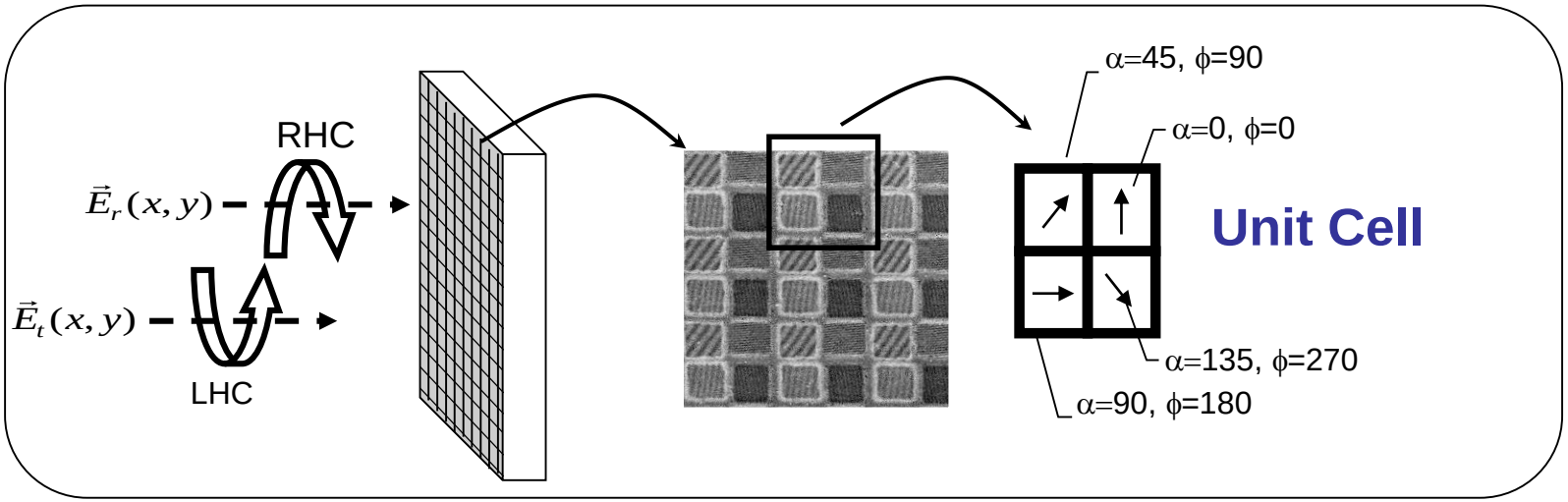


Circular polarized beams (θ) + linear polarizer (α) $\Longrightarrow$ $I = I_T(1+\gamma \mathrm{Cos}\,(\theta + 2\alpha))$

Phase-shift depends on polarizer angle

Kothiyal and Delsile, (1985)

Simultaneous polarization phase-shift – micro-polarizer camera



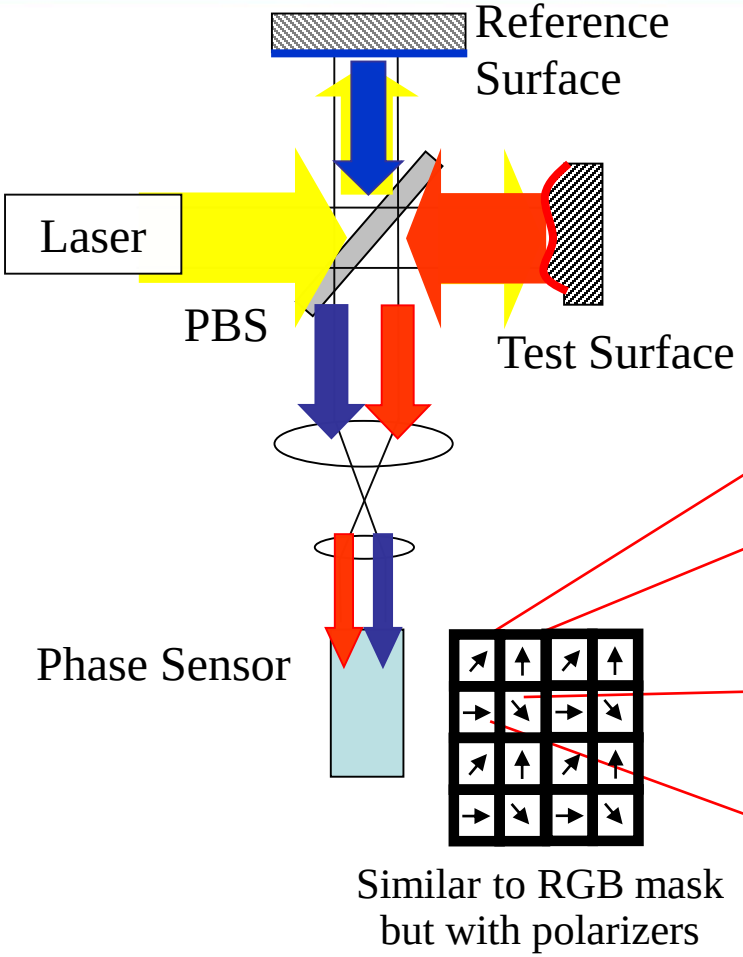
- Array of oriented micropolarizers
- Similar to RGB color mask
- On-axis imaging, broadband wavelength

- **Dynamic Interferometry™**

  "Precision measurement in dynamic environments"

US Patent 7,230,719 (2004)

Dynamic Interferometry

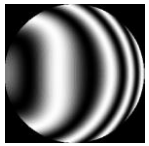


Use polarization to code the beams

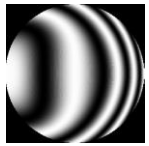
Red = p

Blue = s

$$I_1(x,y) = 1 + Cos[\theta(x,y)]$$



$$I_2(x,y) = 1 - Sin[\theta(x,y)]$$

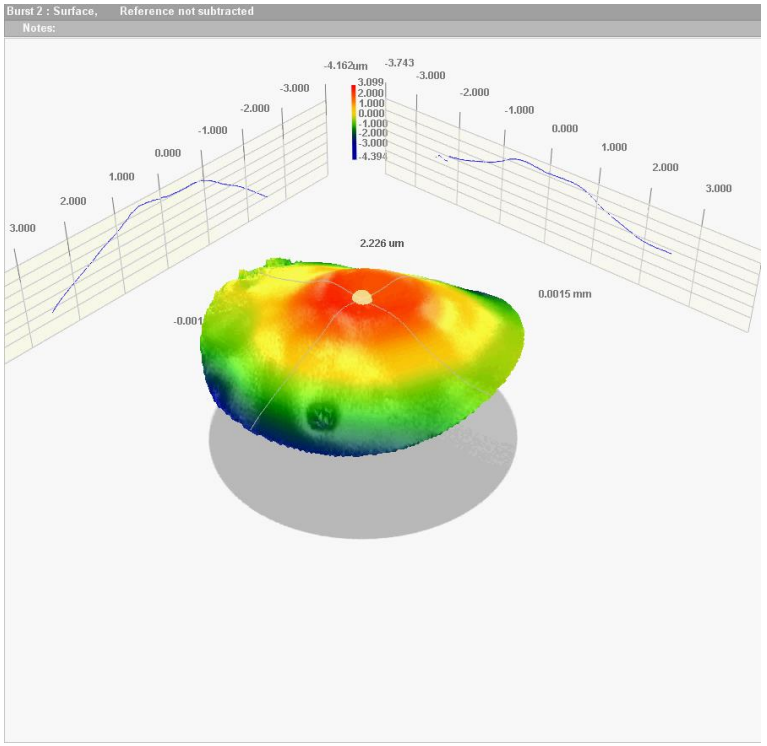


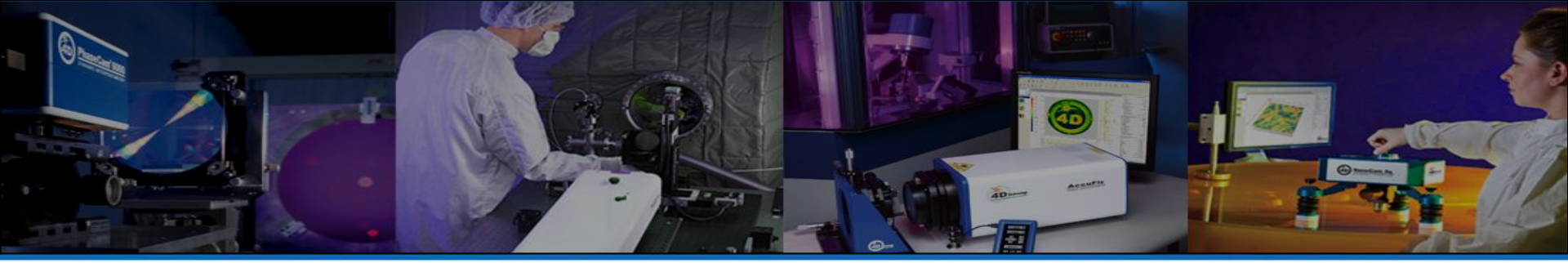
$$I_3(x,y) = 1 - Cos[\theta(x,y)]$$

$$I_4(x,y) = 1 + Sin[\theta(x,y)]$$

Nanoseconds for acquisition!

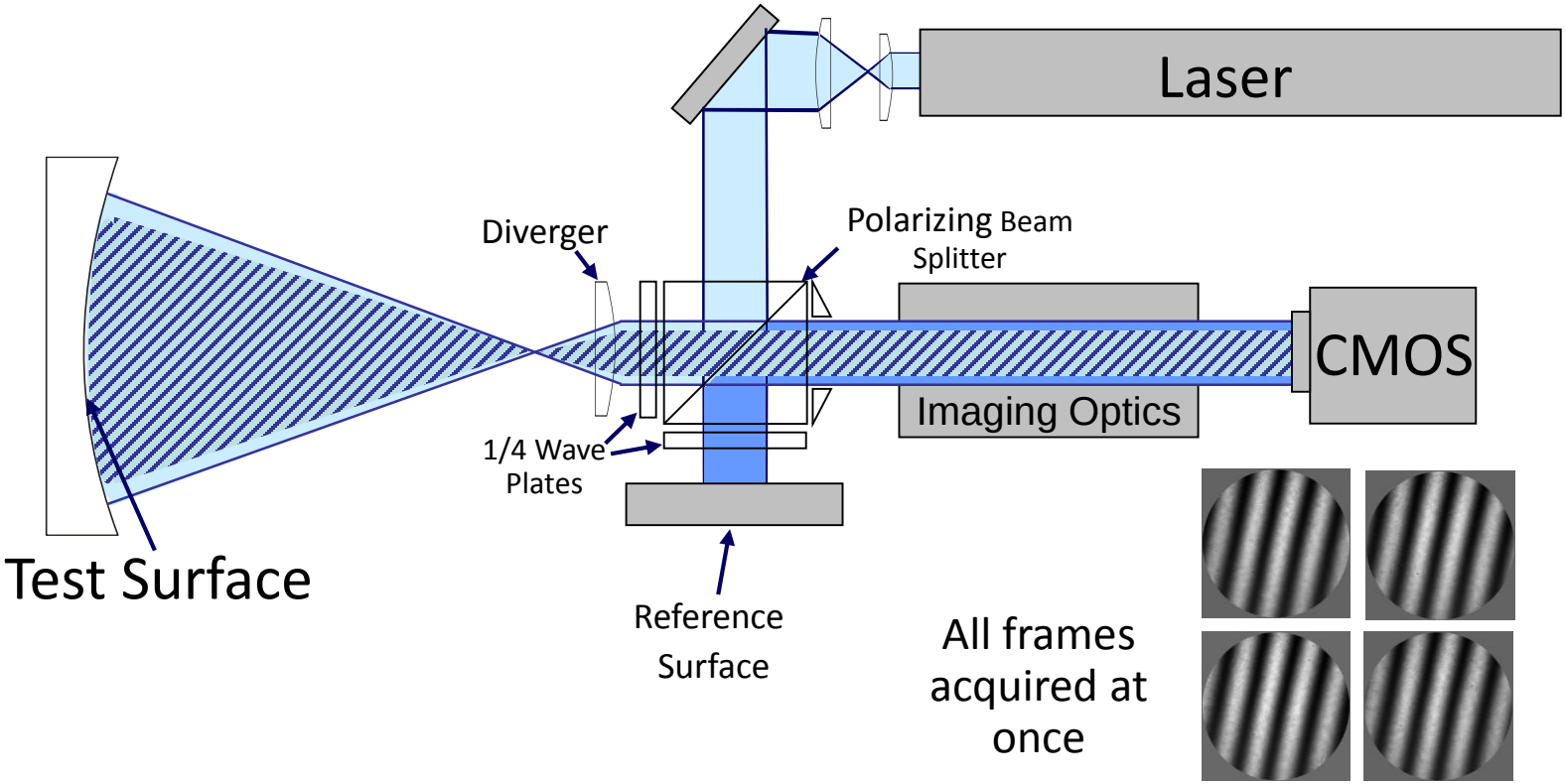
Dynamic Measurement of Human Eye



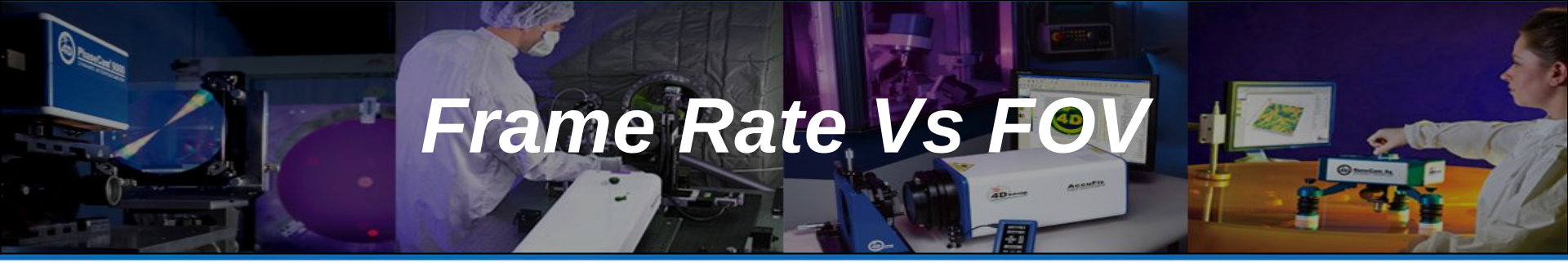


High Speed Interferometer

High Speed Twyman-Green



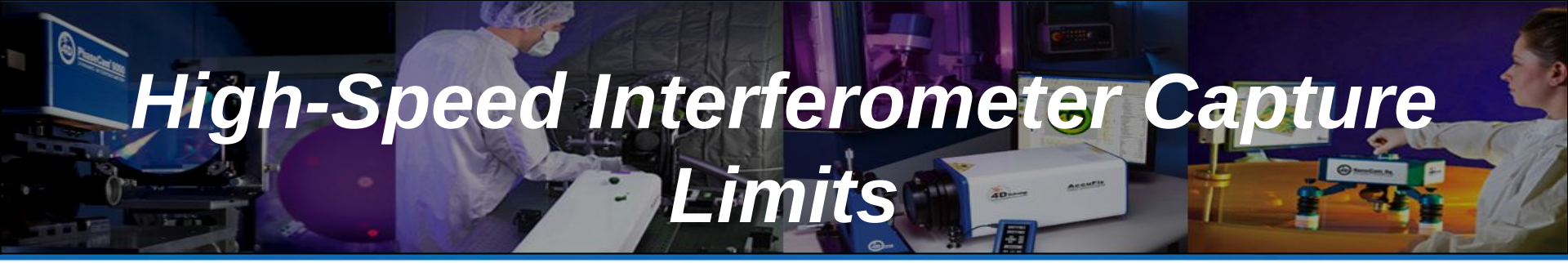
On-axis imaging – works well with fast optics, zoom



Frame Rate Vs FOV

Frame Size	Frame Rate (fps)
1024 x 1024	500
640 x 480	1,800
400 x 300	4,000

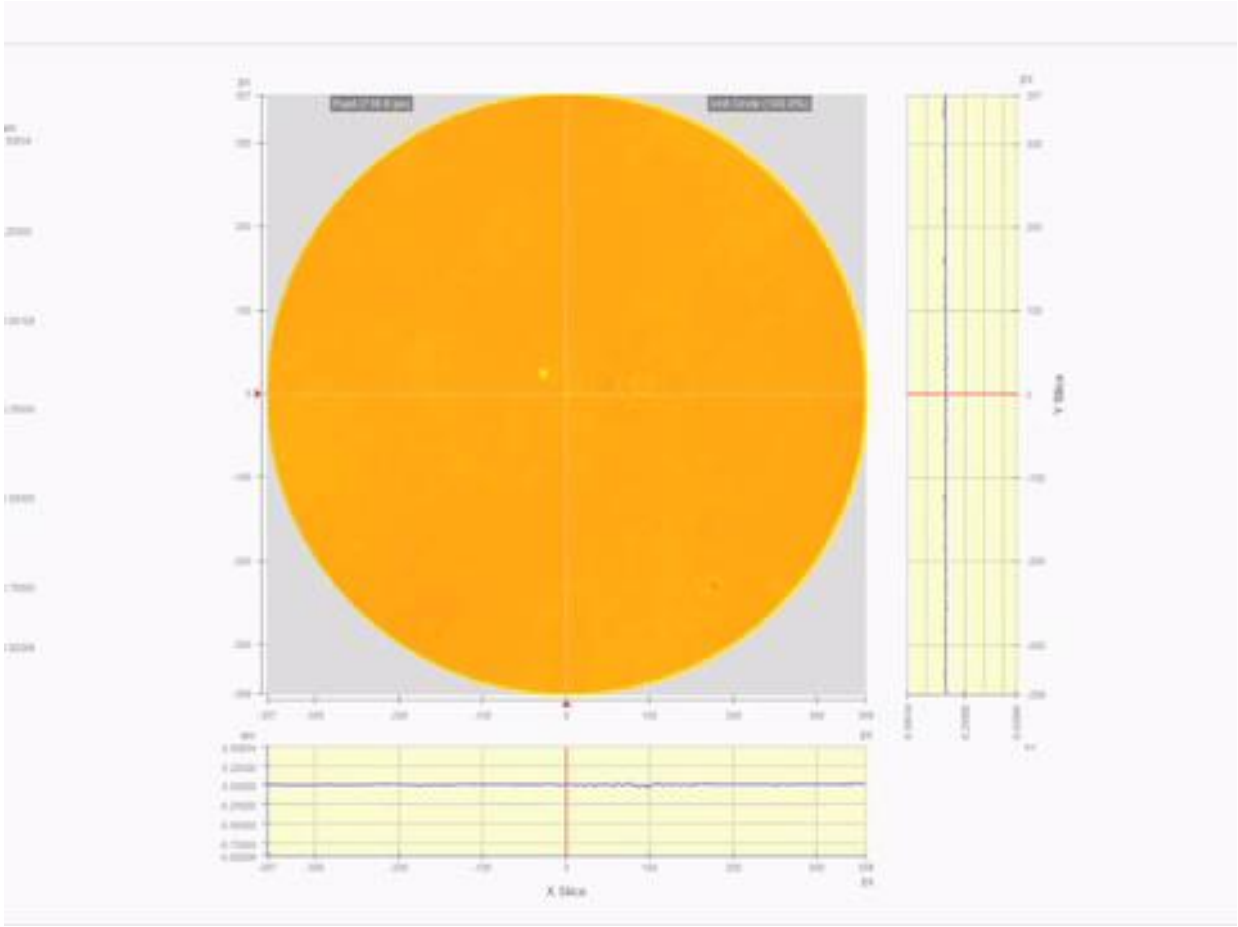
Frame rates greater than 10,000 fps achievable with smaller FOV



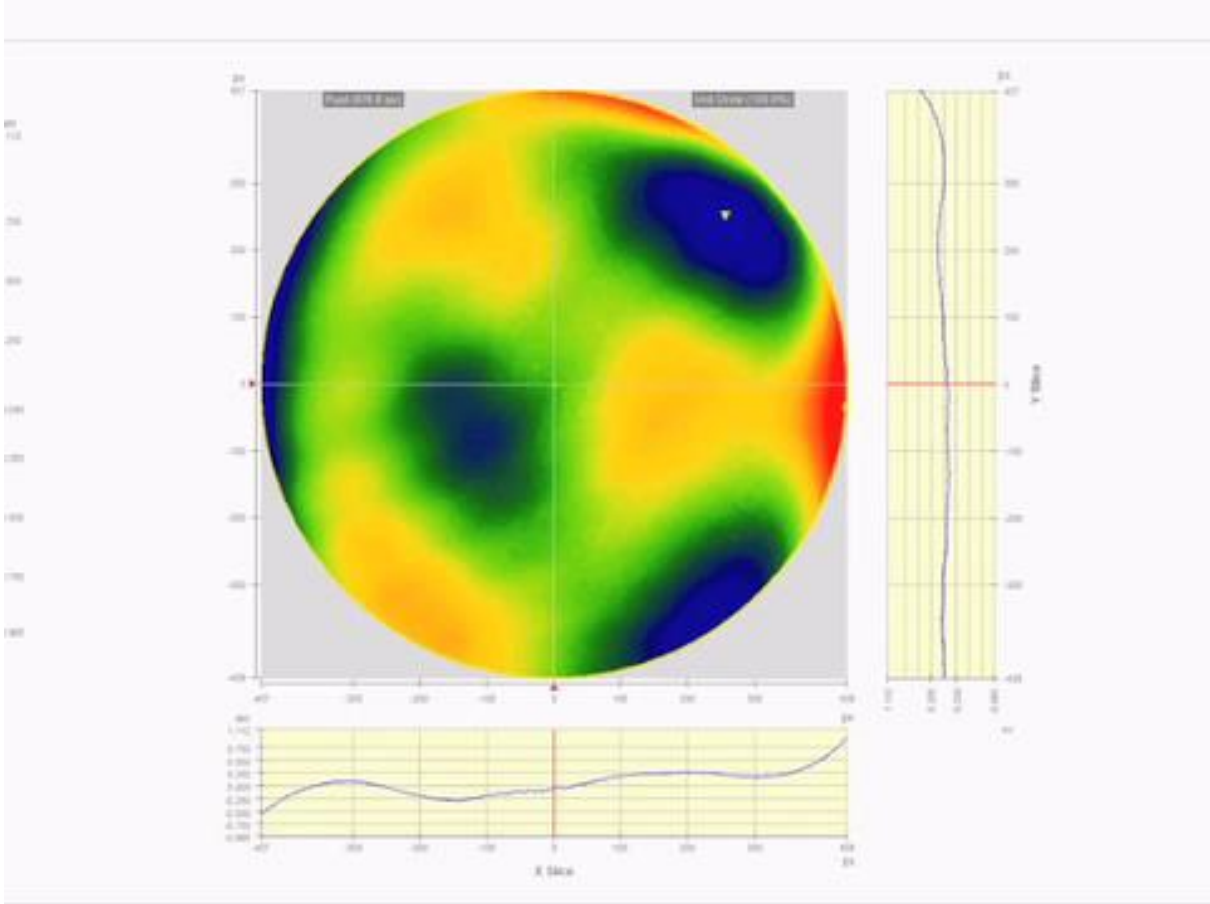
High-Speed Interferometer Capture Limits

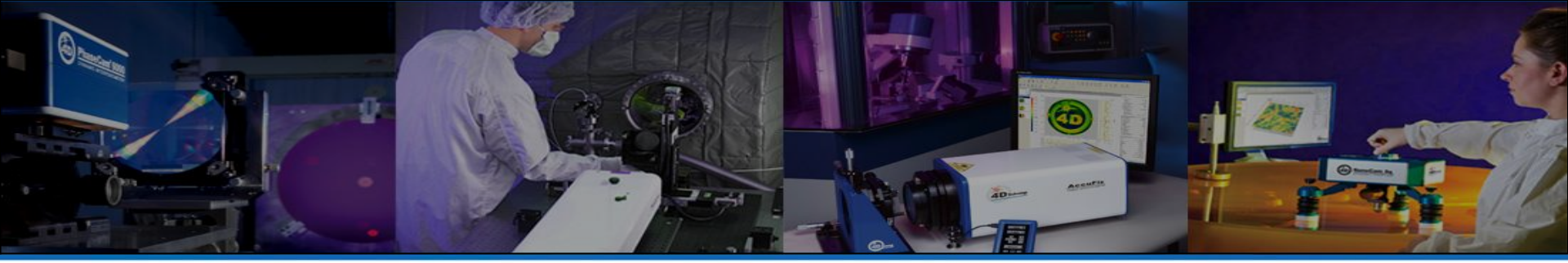
- Data typically collected for 10 seconds for each measurement.
- For each measurement approximately 4.2 GB of data collected.
- The limit on how long a measurement can run is determined by the amount of memory in the data acquisition computer, 20 GB in this instance.

Air Stream, 525 Frames/Second



Water Surface, 525 Frames/Second



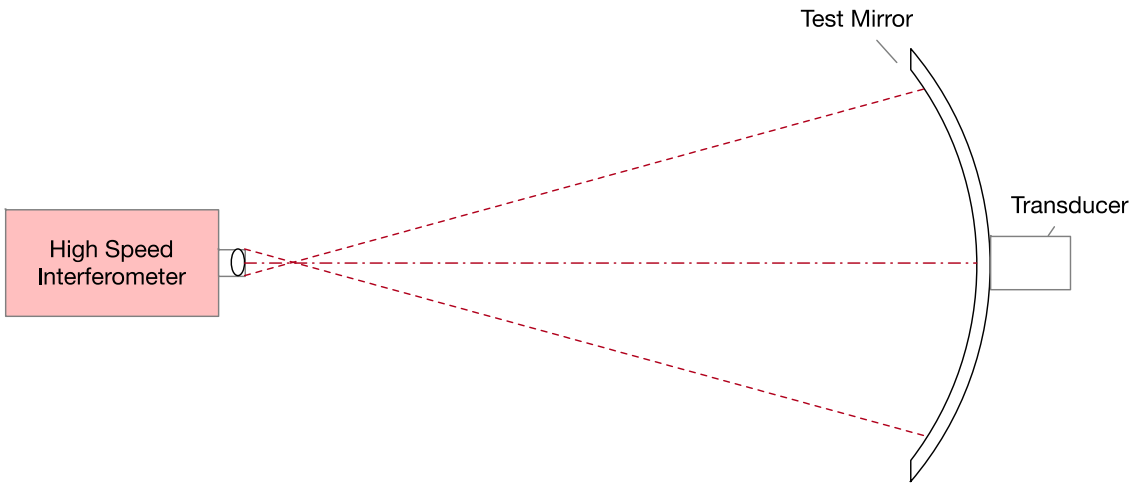


JWST Measurements

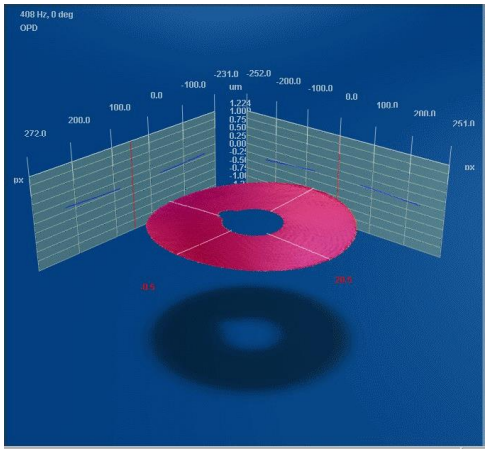
JWST testing

Vibrational Strain Measurements

- Vibrational measurements can validate structural modeling and ensure good performance in flight
- Exo-planet imaging will require extreme stability
- 5000 fps dynamic interferometer used to characterize vibration

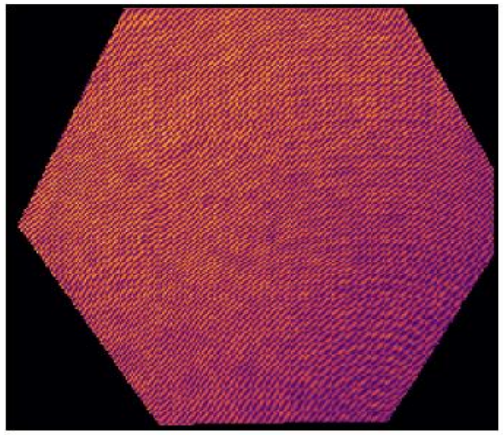


Mirror excited at 400Hz

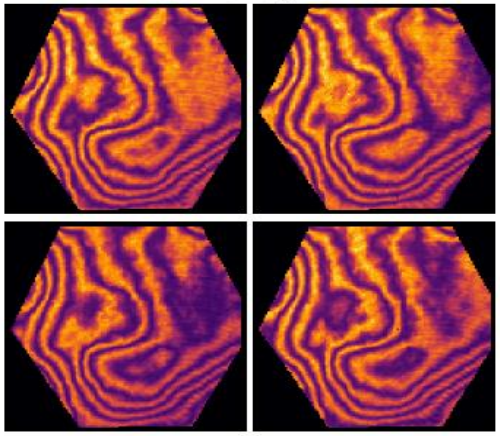


Single High Speed Interferometer Measurement

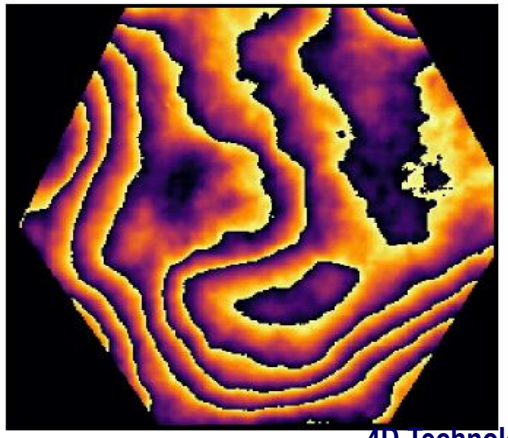
Raw Frame



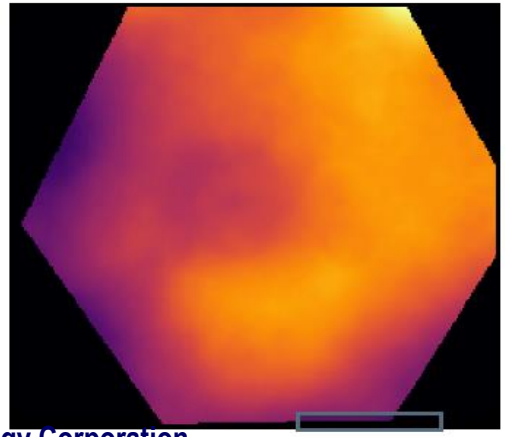
Instantaneous Phase-Shifted Interferograms



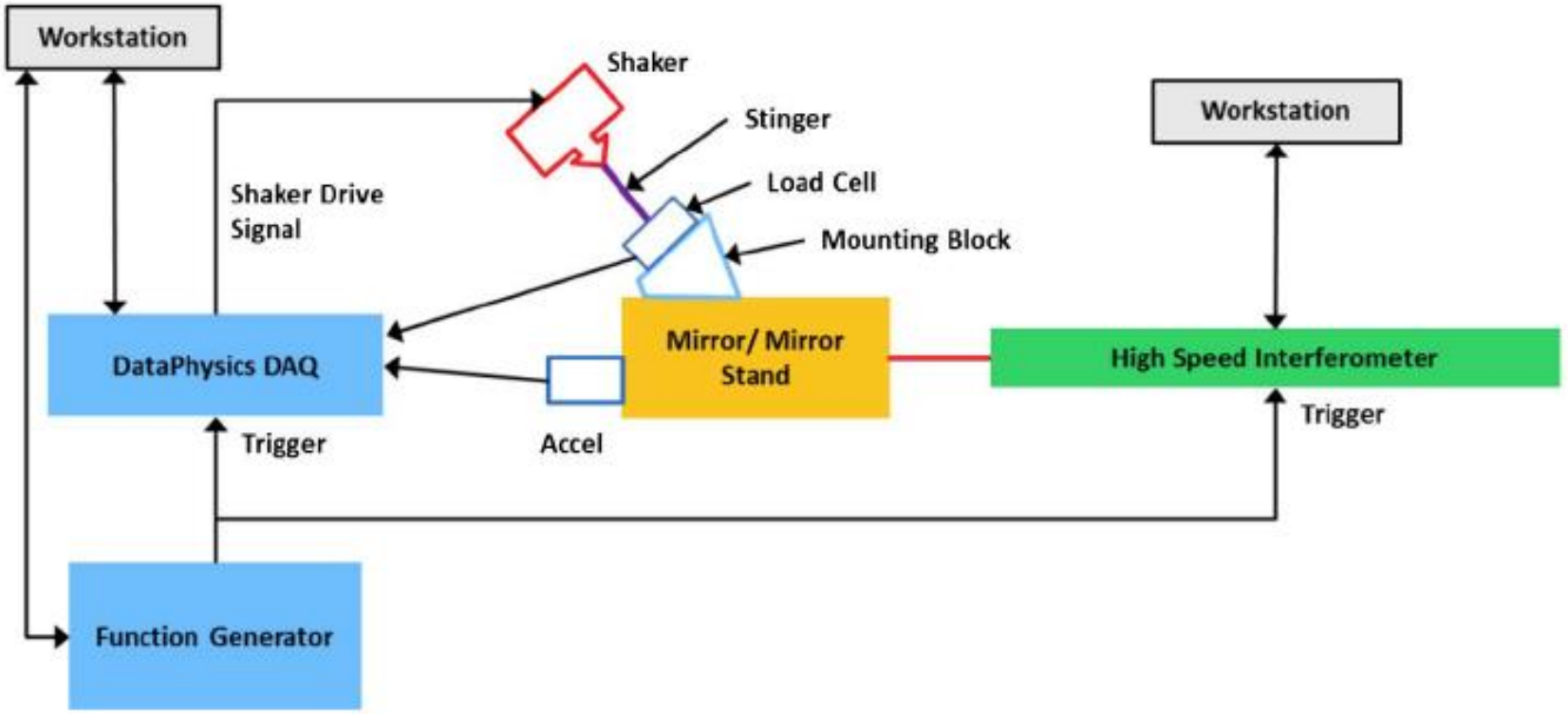
Reconstructed Wrapped Phase



Surface



Test Setup

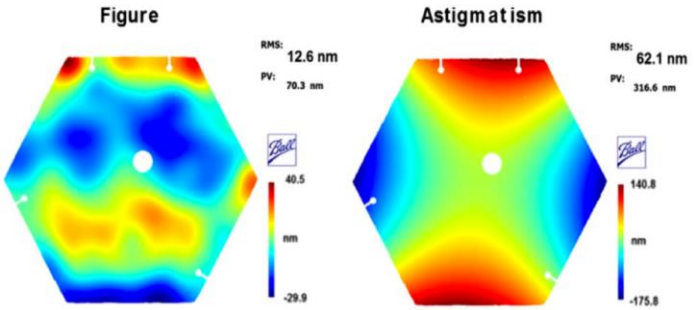

Workstation
Shaker
Stinger
Load Cell
Mounting Block
Shaker Drive Signal
Workstation
DataPhysics DAQ
Mirror/ Mirror Stand
High Speed Interferometer
Trigger
Accel
Trigger
Function Generator

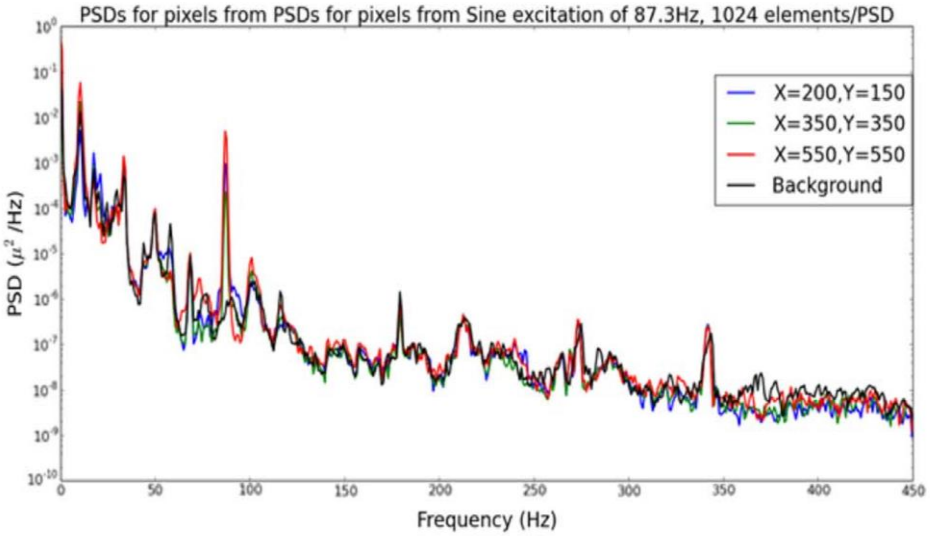
Vibrational Strain Measurements - JWST

COMPARISON OF SSDIF MEASUREMENT TO XRCF MEASUREMENT

SSDIF compensated for:
- RoC actuation residual

XRCF compensated for:
- gravity tilt on test stand
- reference sphere measurement
- window vacuum effects
- CGH substrate error
- RoC actuation residual
- CGH to mirror spacing error

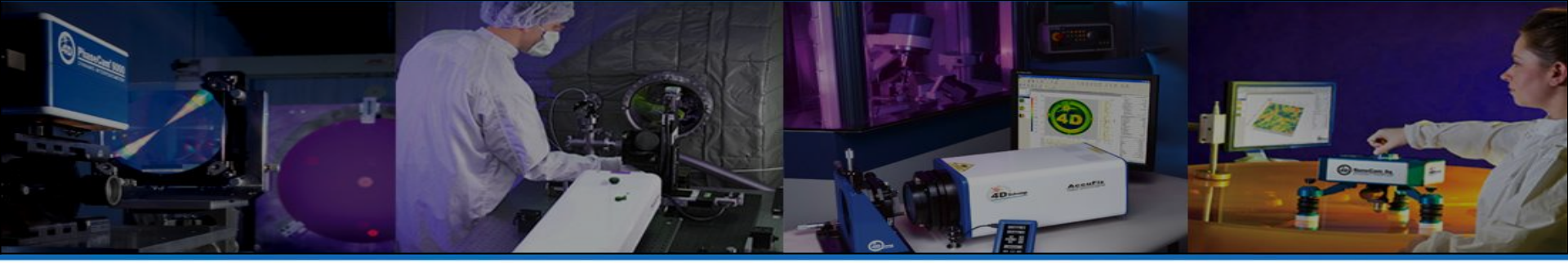




Saif, et al., "Nanometer level characterization of the James Webb Space Telescope opto-mechanical systems using high-speed interferometry," Appl. Opt. 54 (2015)

Measurement Results

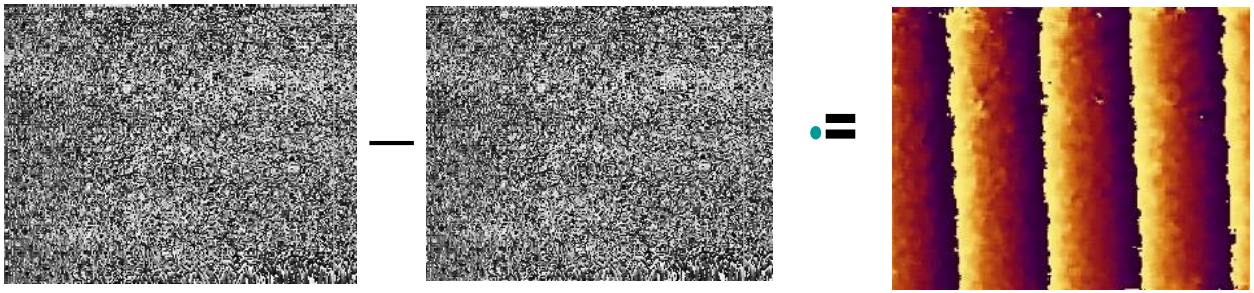
- Interferometer is capable of tracking large absolute motion (i.e., piston) of the mirror's entire surface over orders of magnitudes of wavelengths displacement.
- Preliminary tests have shown it to be capable of measuring dynamic effects on the level of tens of picometers reliably.
- This measurement capability is very important for future space optics and an interferometer combining the high speed capability and the ESPI is currently being designed and constructed.



Beyond JWST – Combine High Speed Interferometer with ESPI

James Webb Space Telescope Back Structure

ESPI Measures Changes In Diffuse Structures



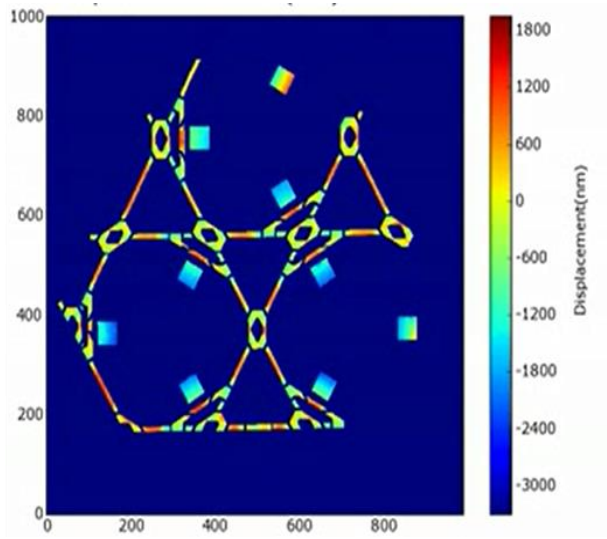
$$DOPD = \frac{l}{2p} ArcTan\left(\frac{[I_{23} - I_{21}][I_{14} - I_{12}] + [I_{11} - I_{13}][I_{24} - I_{22}]}{[I_{11} - I_{13}][I_{21} - I_{23}] + [I_{14} - I_{12}][I_{24} - I_{22}]}\right)$$

Provides differential measurement of diffuse and specular surfaces.

Structural/Thermal Strain Measurements

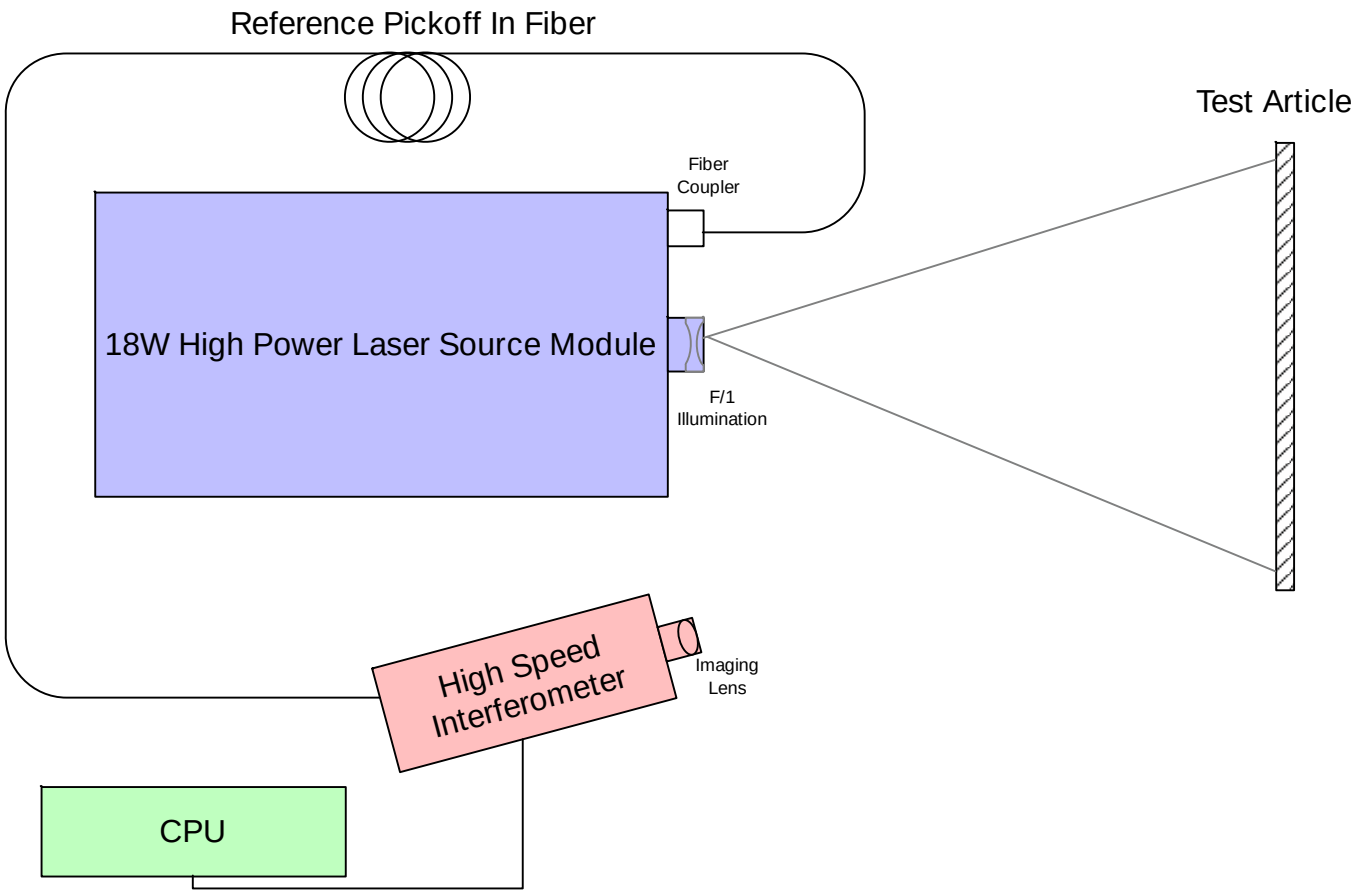
- Thermal response of structure key in maintaining alignment in space.
- Speckle interferometry – change in shape of diffuse structures.
- Requires significant laser power

100's nm/days



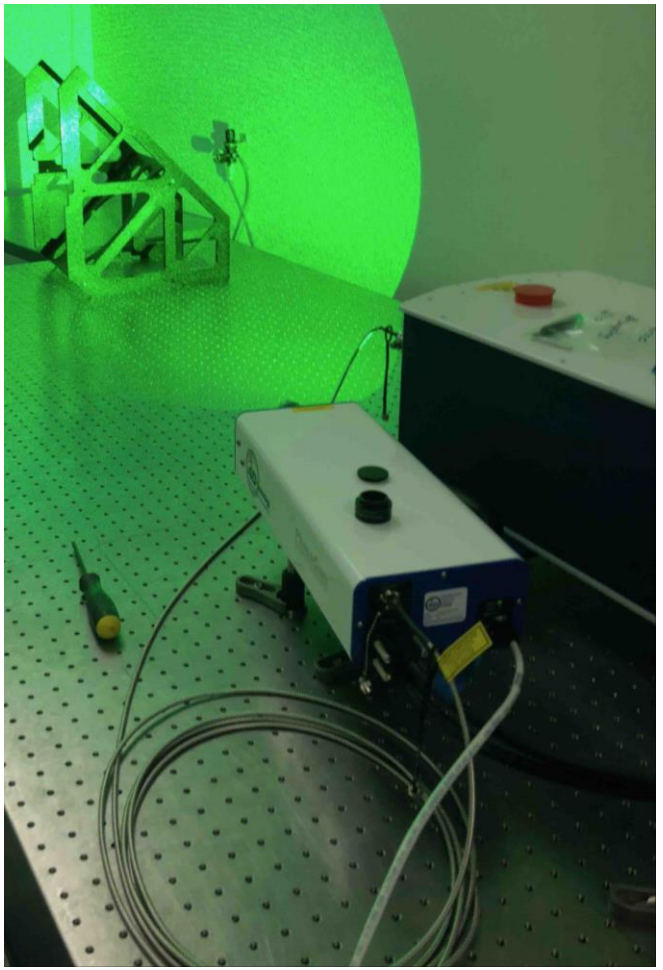
Babak Saif, et al. "Measurement of large cryogenic structures using a spatially phase-shifted digital speckle pattern interferometer," Appl. Opt. 47, (2008)

High Speed ESPI Layout



High Speed ESPI Status & Images

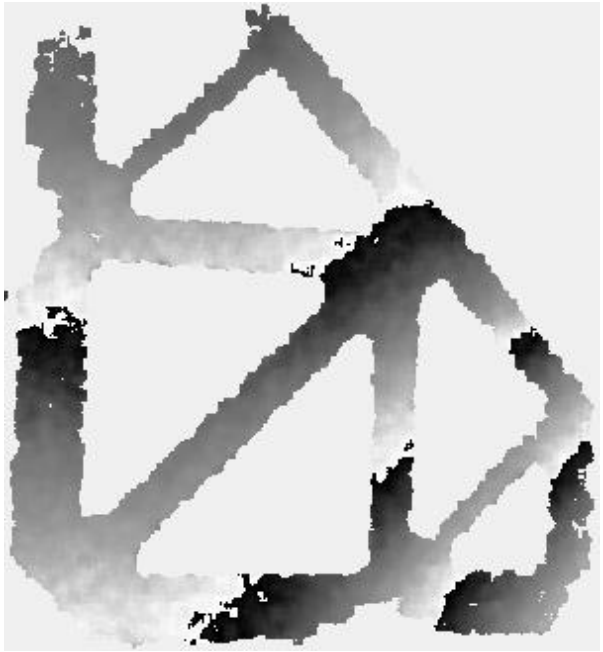
- System Build Complete
- Software Release Candidate in Testing
- Capability Evaluation in Process
- Quality Testing This Month



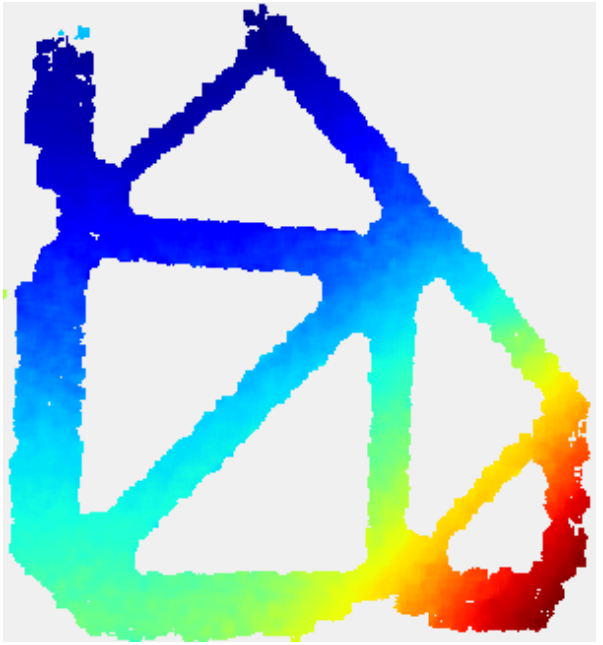
Measurement of Anodized AL Support Structure

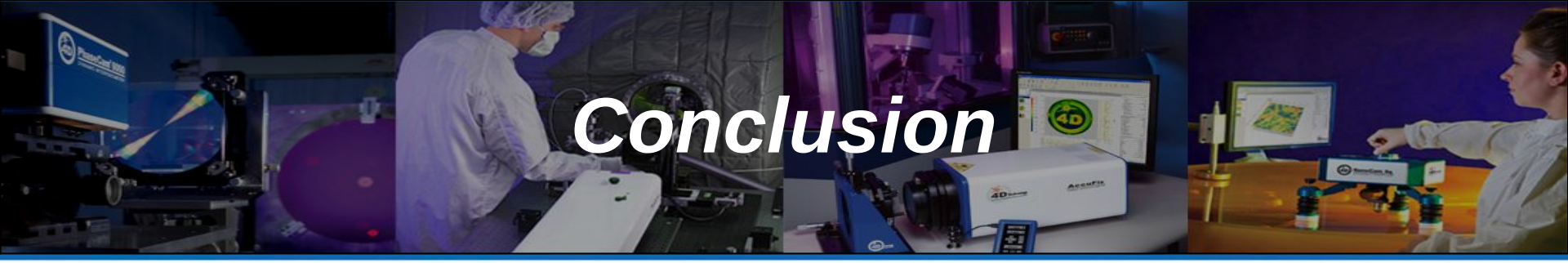
Interference Pattern

Wrapped Phase



Surface Change





Conclusion

- High Speed Interferometry On JWST
  - Uses Dynamic Interferometer
  - Preliminary Tests Measured Dynamic Effects On the Level of Tens of Pico-meters
- Next Generation
  - Combine High Speed Interferometer with ESPI Measurements
  - Initial System Build Complete
  - System Evaluation in Process