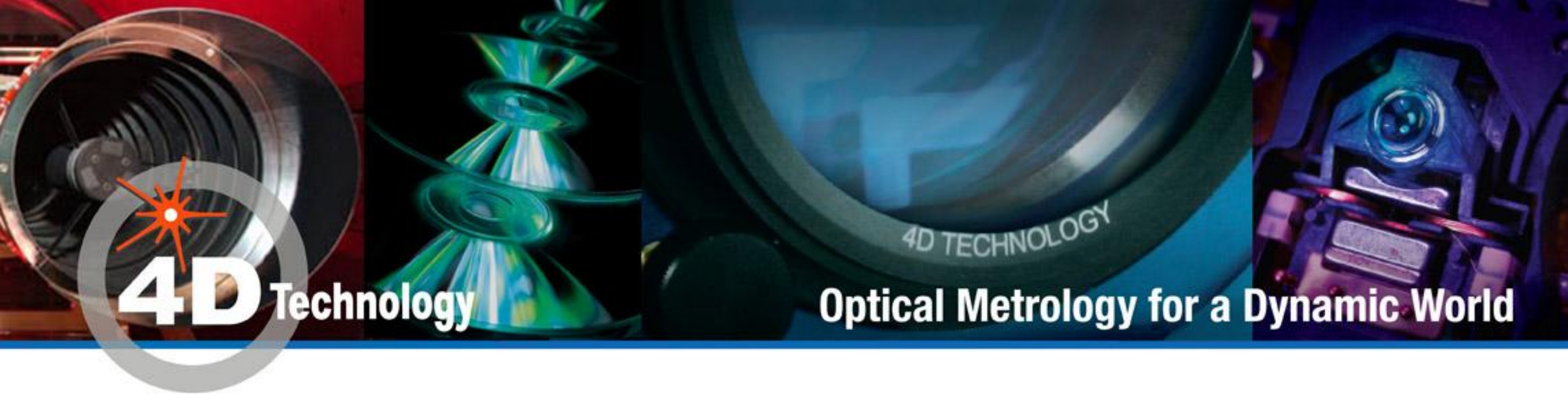

In-Situ Extended Lateral Range Surface Metrology

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NASA Phase I SBIR: NNX11CF45P

June 21, 2011

•Small
•Business
•Innovation
•Research

In-Situ Extended Lateral Range Metrology

4D Technology Corporation
Tucson, Arizona

NanoCam Sq with on-optic tripod stand

INNOVATION

Dynamic Optical Profiler for surface roughness characterization

Non-contact, sub Angstrom surface roughness measurements.
3 decades of spatial frequency response.
Vibration immunity allowing in process measurements.

TRL Assessment from Start to End of Project: 2.5 ; 3.5

TECHNICAL ACCOMPLISHMENTS

- Advanced prototype stage
- Sub Angstrom measurement precision demonstrated.
- Algorithm developed to allow single measurement shot noise limited performance.
- Light source developed allowing < 100 usec exposures when measuring uncoated optics
- Demonstrated on-tool performance
- Extended range lateral scanning demonstrated

FUTURE PLANS

- Incorporation of fast focus and tilt sensor.
- Improvements to interference objectives.
- Refine fine motion stitching algorithms through experimentation and modeling
- Evaluate alternative image sensors

GOVERNMENT/SCIENCE APPLICATIONS

- Super-smooth optics for LIGO, NIF, WFIRST, LISA & ICEsat
- Large optics such as LSST, GMT, TMT, ELT, JDEM
- X-ray, synchrotron, DUV and EUV optics such as IXO
- Precision machined surfaces (medical, automotive)
- Engineered surfaces (flat panel and flexible displays, MEMS, Semiconductor

COMMERCIALIZATION

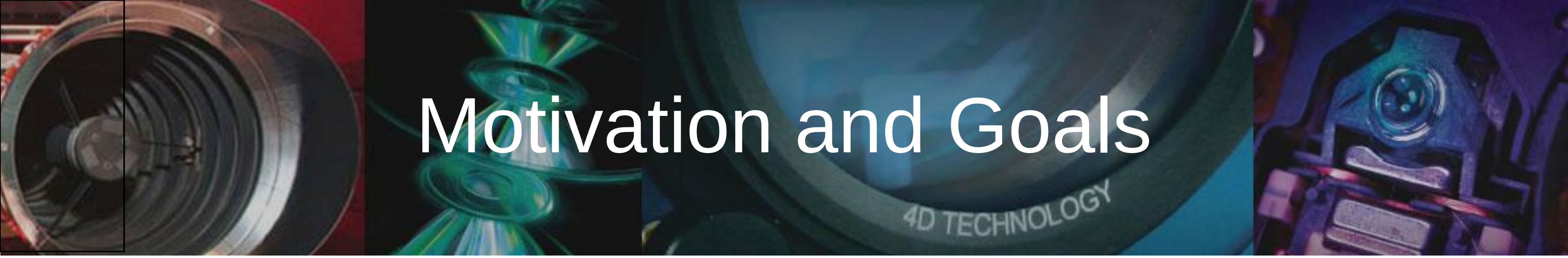
- Product name: NanoCam Sq.
- Primary target market: Large optic manufacturing, semiconductor, flat panel display.
- Significant interest generated at tradeshows for non-stitching version.

Marshall Space Flight Center
Subtopic Name, Number
June 21,2011

Approved for Public Release

Outline

- Motivation and Goals
- Challenges and Proposed Solutions
- Pixelated mask phase sensor
- 4D optical profiler
- Instrument performance
- Fine motion stitching
- Focus and tip/tilt sensing



Motivation and Goals

Motivation

Methods for evaluating surface roughness on in-process optics is difficult and time consuming due to size and performance limitations of currently available instruments. This is especially true for the manufacture of large scale optics.

Goals

A high performance optical profiler for surface roughness characterization which is:

1. Capable of being used in-situ during the optical polishing process.
2. Sub Angstrom precision.
3. > 3 decades spatial frequency response.

Challenges

❑ Vibration / Positional Stability

1. Vibration isolation / immunity required
2. Short depth of focus

❑ Measurement Noise

1. Shot noise
2. Instrument related noise

❑ Size and weight

1. Light and compact in order to facilitate high accuracy positional control and ease of handling.
2. Weight and size restriction of tool.
3. Heat dissipation limitations.

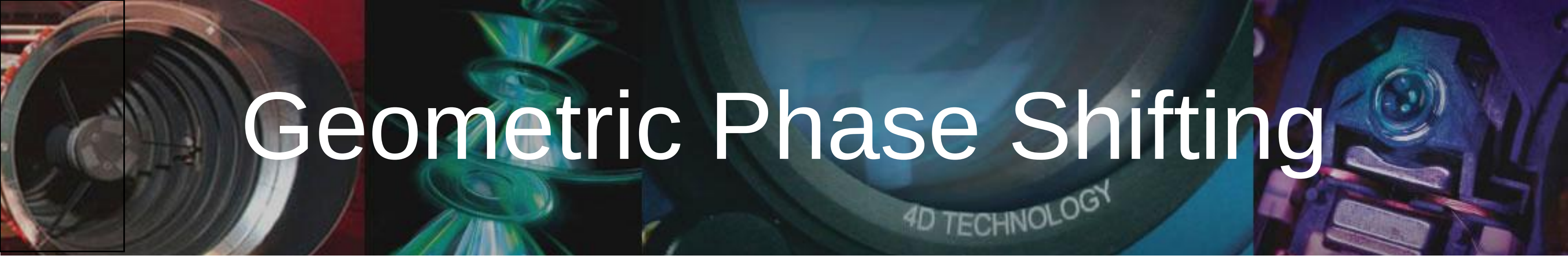
Solution

Optical profiler with 4D technology's pixilated phase sensor, high brightness extended source and autofocus sensor.

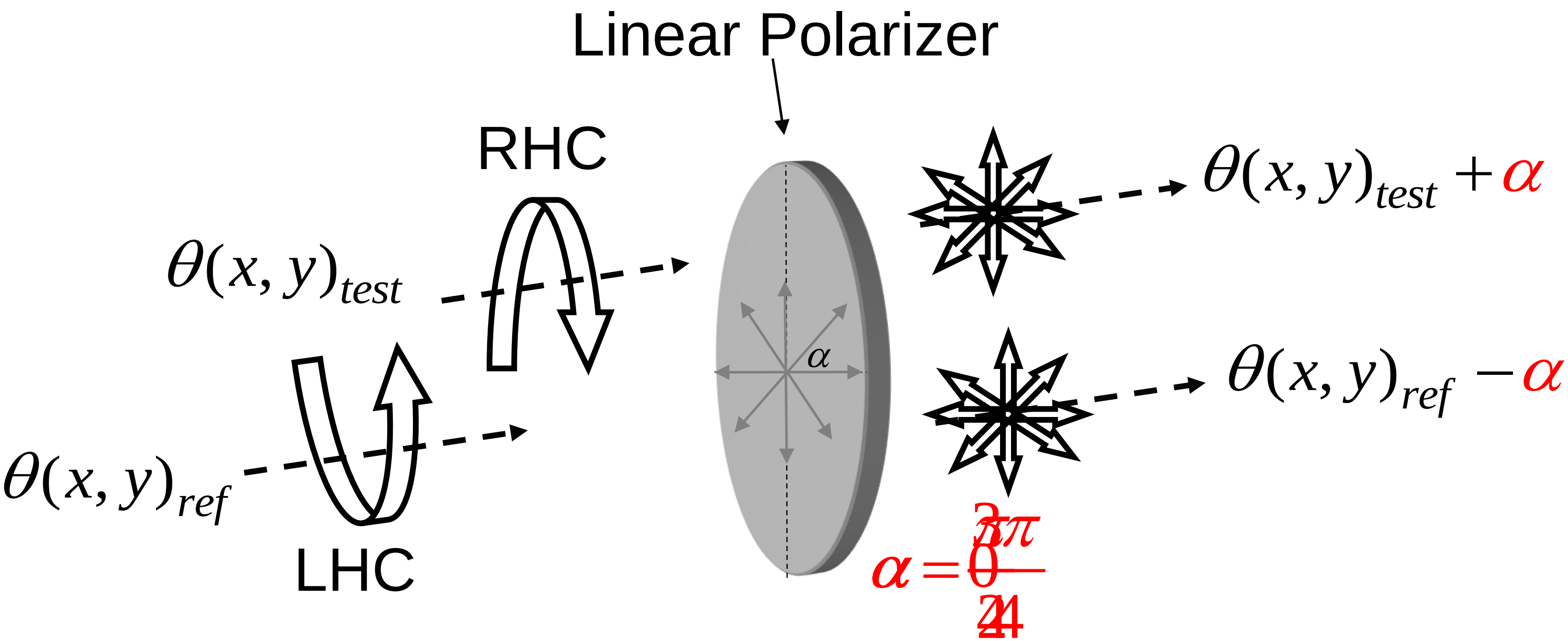
- Pixelated phase sensor
  1. Vibration immunity through single shot phase measurements at <100 usec exposure.
  2. Rapid independent measurements allow extensive averaging
- High brightness source
  1. Small form factor, low power, short duty cycle (heat)
  2. Allows max camera signal at min exposure. Shot noise minimized.
  3. Limited spatial and temporal coherence mitigates noise.
- Folded beam path with tight component integration
- Low noise 12 bit, 1.4Mpix camera

Polarization Challenge

- Pixelated phase sensor requires orthogonally polarized test and reference beams.
  1. High NA objectives necessitate use of Linnik style polarization interference objectives.
  2. Folded optical path makes polarization control challenging
  3. Polarization aberrations result in phase calculation errors which necessitated new algorithm development
- Polarization allows beam ratio adjustment for maximum fringe contrast across a wide range of samples.



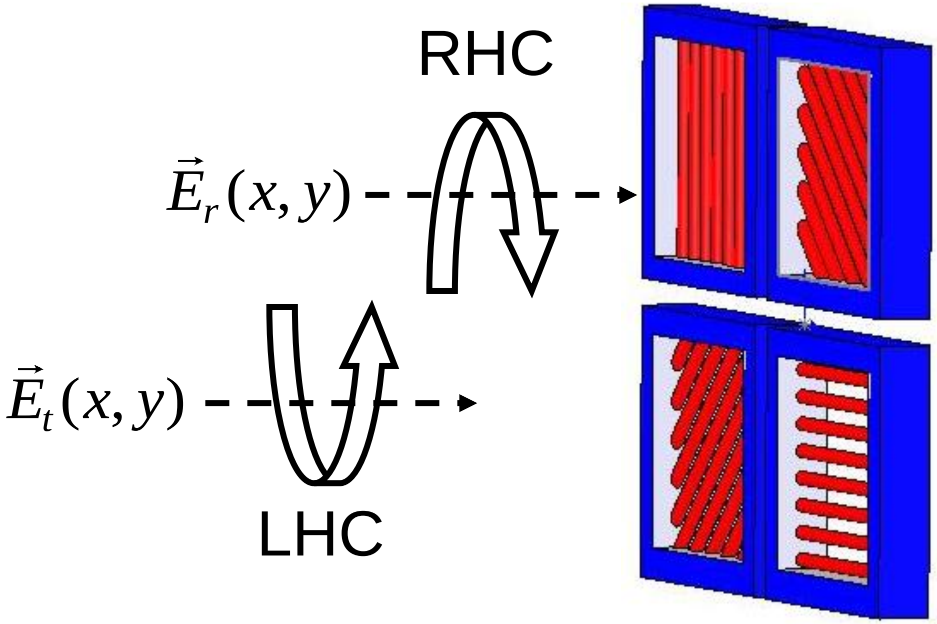
Geometric Phase Shifting



$$\text{Phase Difference} = \theta_{test}(x,y) - \theta_{ref}(x,y) +$$

Pixelated Mask Spatial Carrier

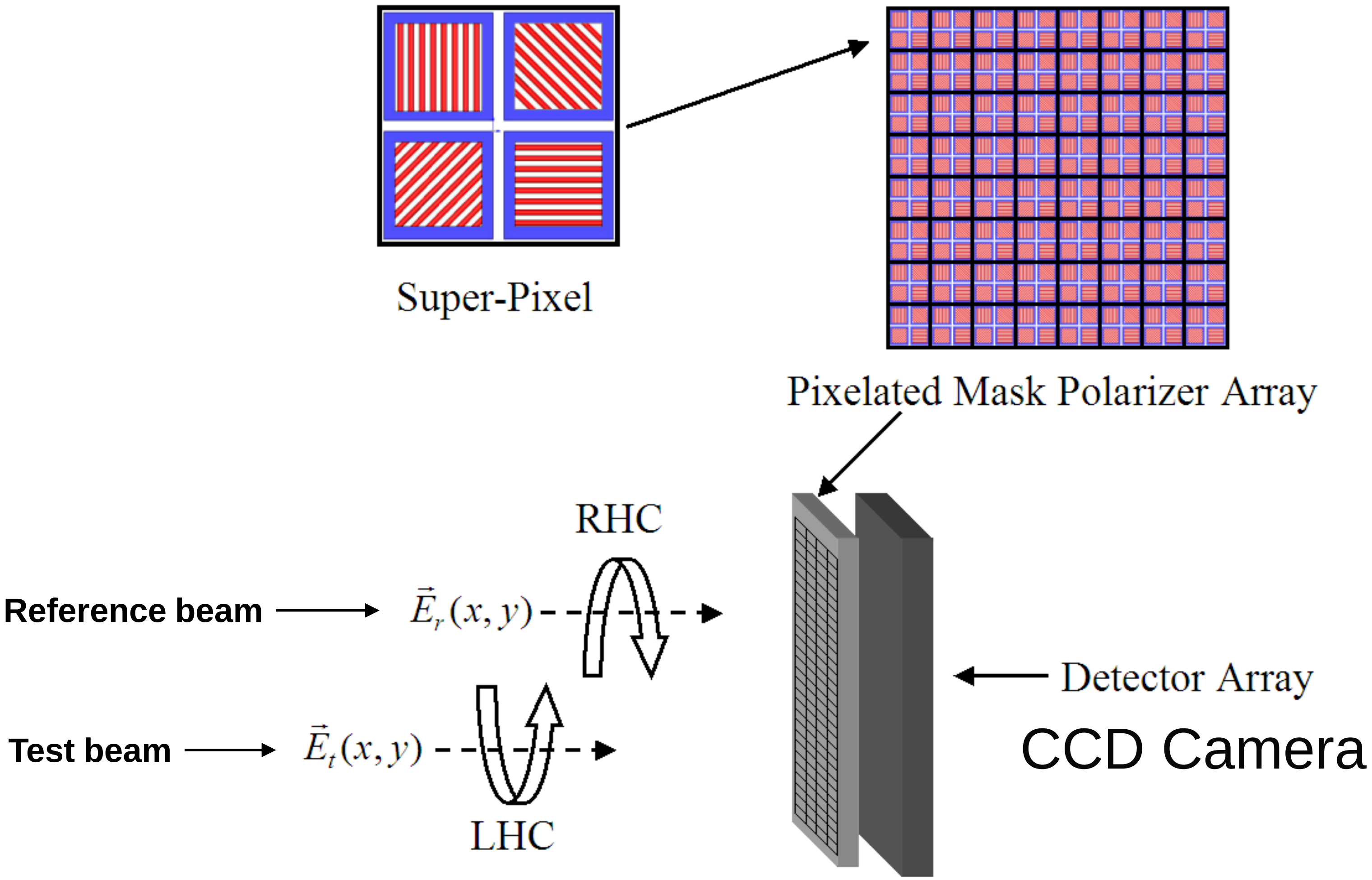
Super-Pixel



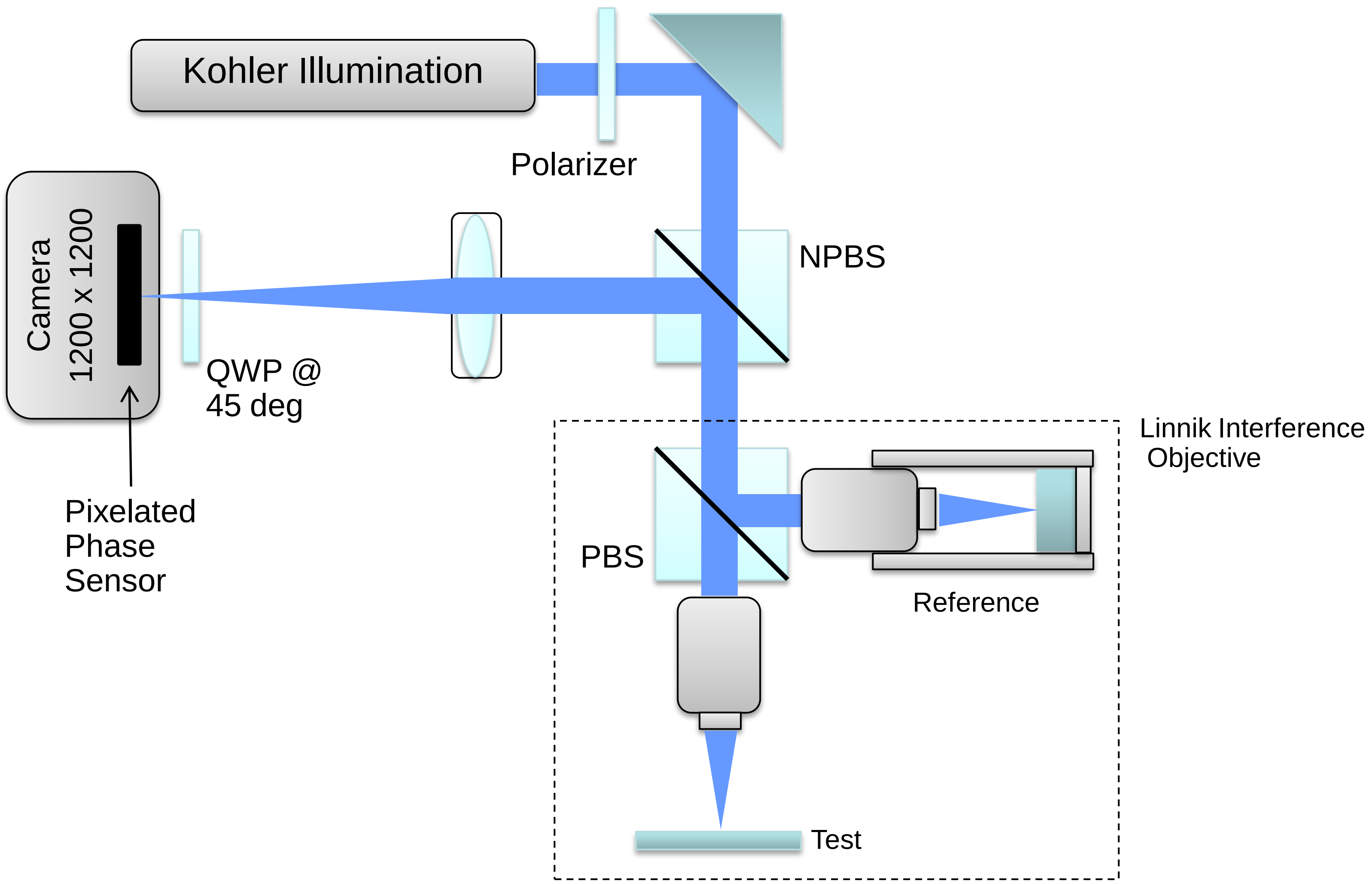
Introduced Phase Shift

$\phi_1 = 0$	$\phi_2 = \pi/2$
$\phi_4 = \frac{3\pi}{2}$	$\phi_3 = \pi$

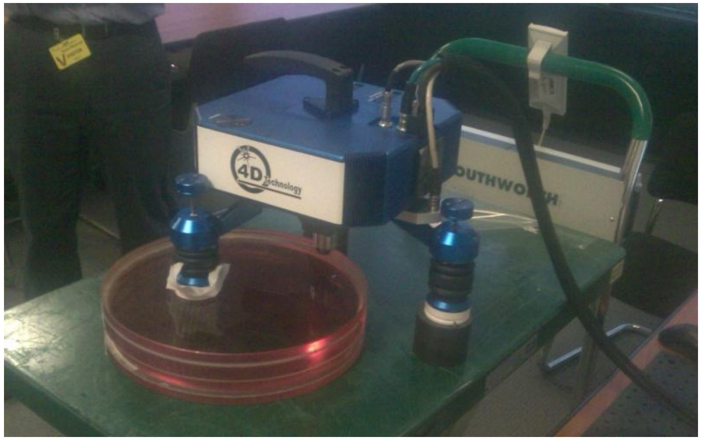
Pixelated Mask Spatial Carrier

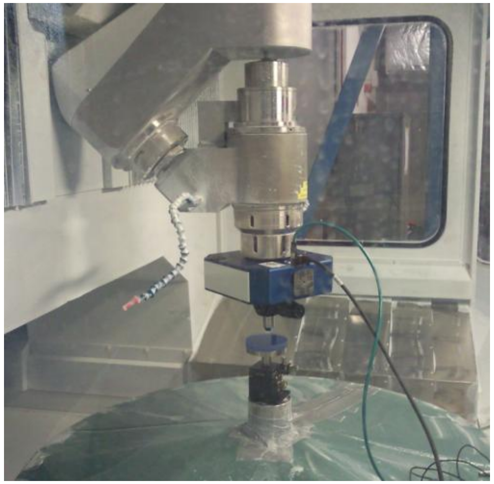


Profiler Functional Diagram



Engineering Prototype





Courtesy of Zeeko Ltd

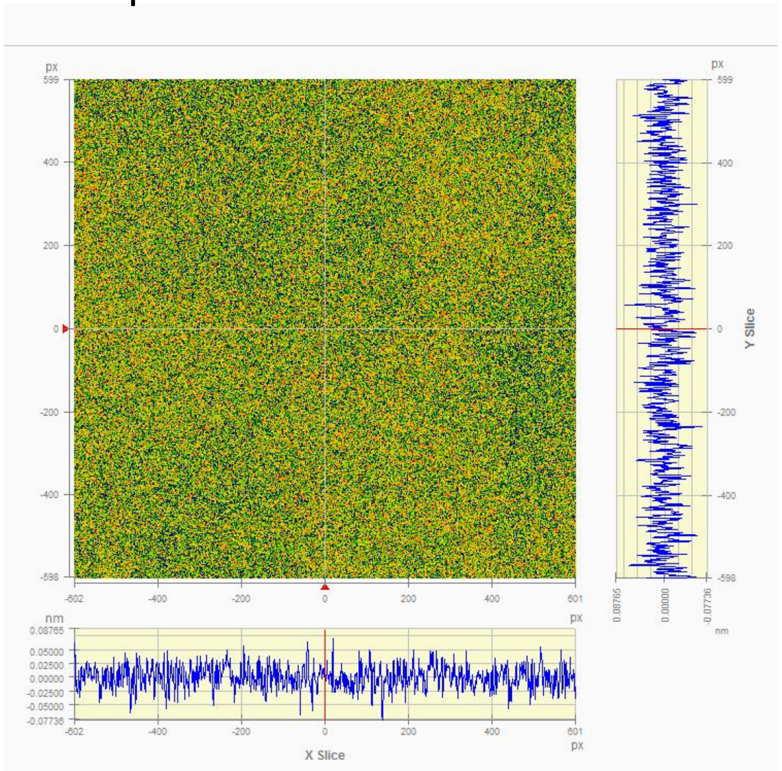
Measurement Performance

- Shot Noise = 0.55 nm RMS single measurement
- Uncalibrated accuracy: 1 nm RMS 3.4 nm PVq
  1. Low order (shape): 0.98 nm RMS 3.0 nm PVq (calibrate)
  2. High order (roughness): 0.1 nm RMS 0.4 nm PVq
- 16 Averages
  1. RMS Precision: 0.08 nm RMS
  2. RMS Repeatability: 0.005 nm RMS

Long Averages
(Difference Measurements)

500 Average

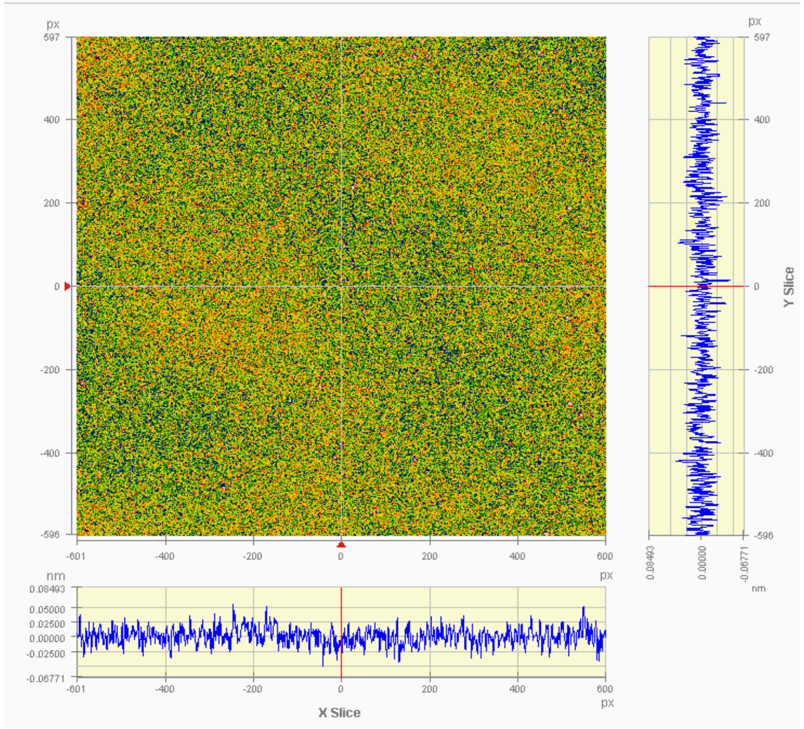
PVq = .083 nm RMS = .0214 nm



Measurement Time = 30 seconds

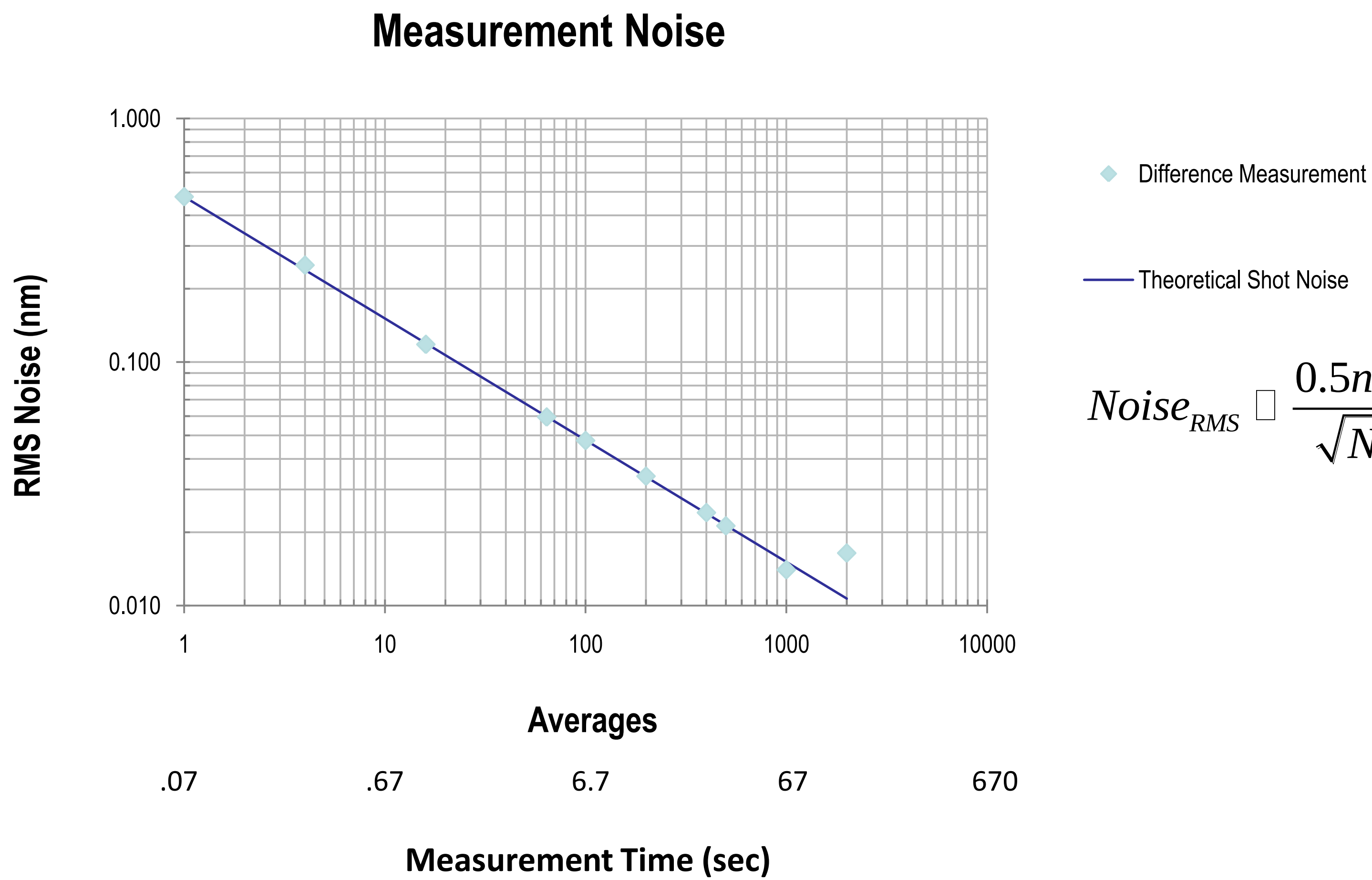
1000 Average

PVq = .054 nm RMS = .014 nm



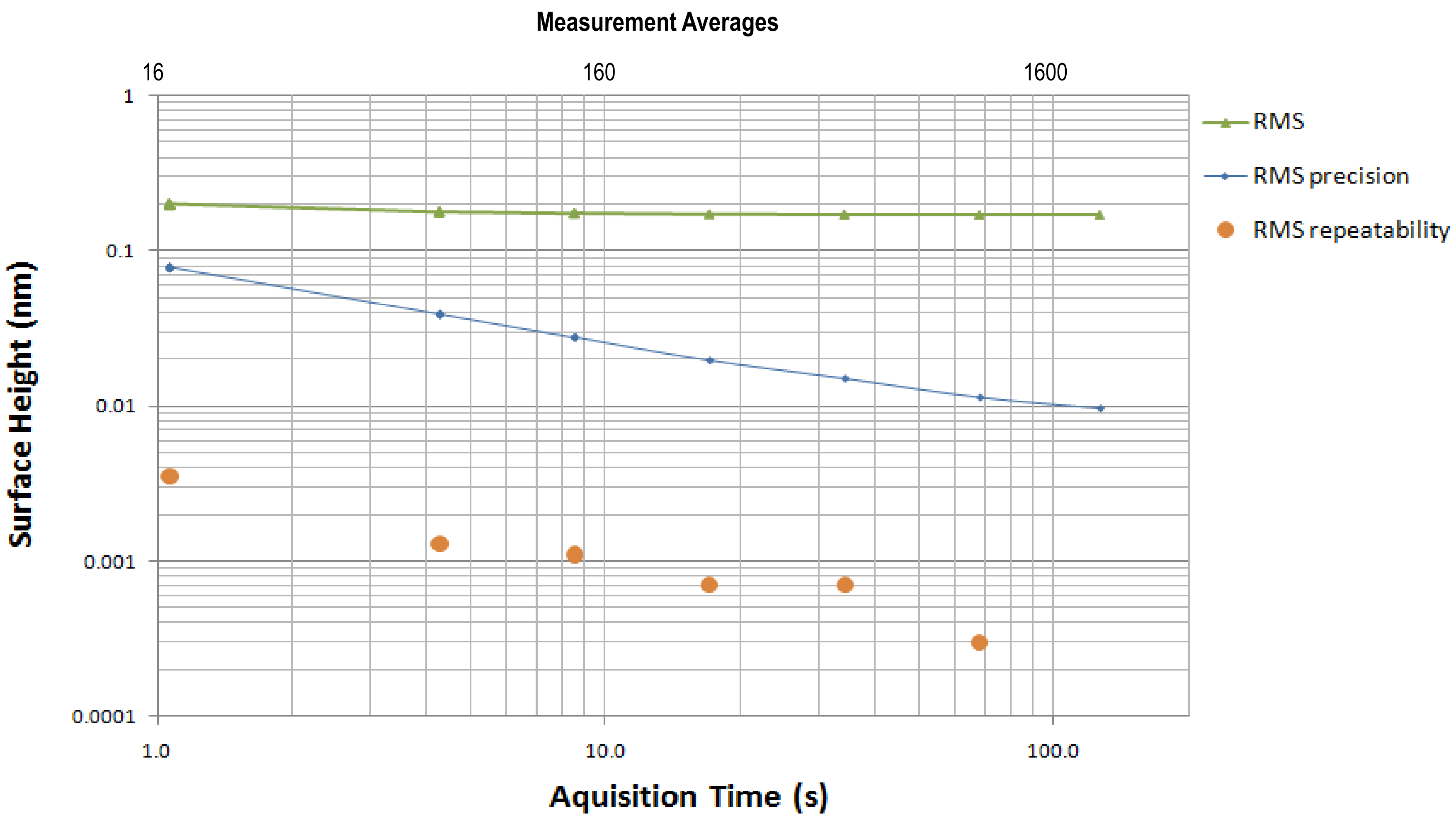
Measurement Time = 60 seconds

Measurement Noise
(Difference Measurement Method)



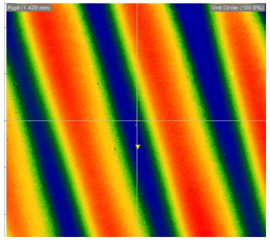
$$Noise_{RMS} \approx \frac{0.5nm}{\sqrt{N}}$$

Super Smooth Measurement Performance



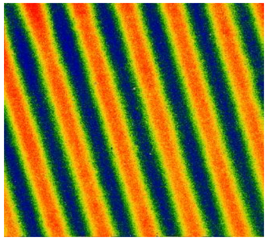
Single Shot Print through

(Super Smooth Surface)



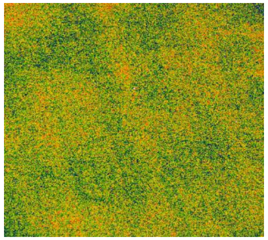
Standard Calibration

15 nm PV



Flat Field Calibration

3 nm PV

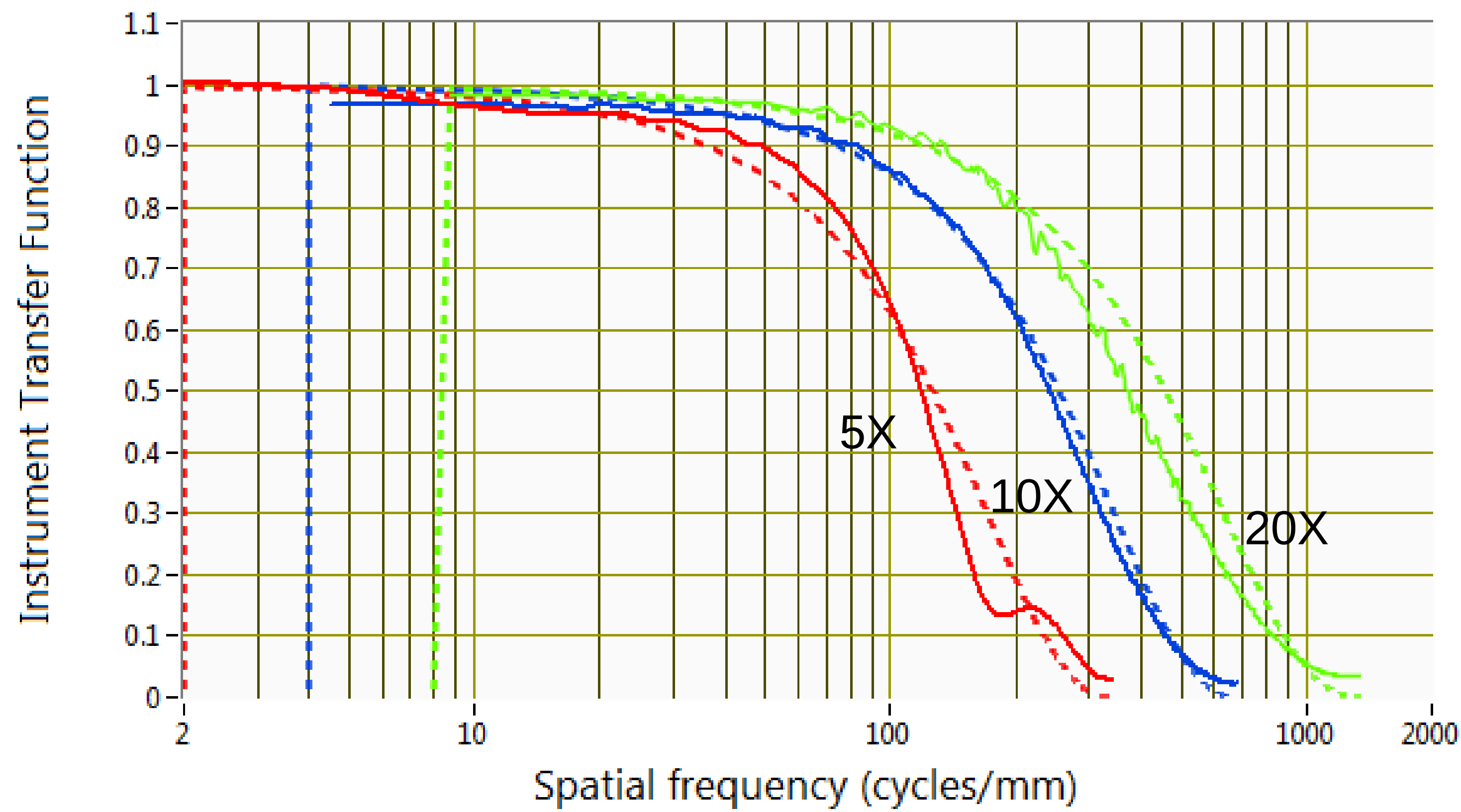


E2C Calibration

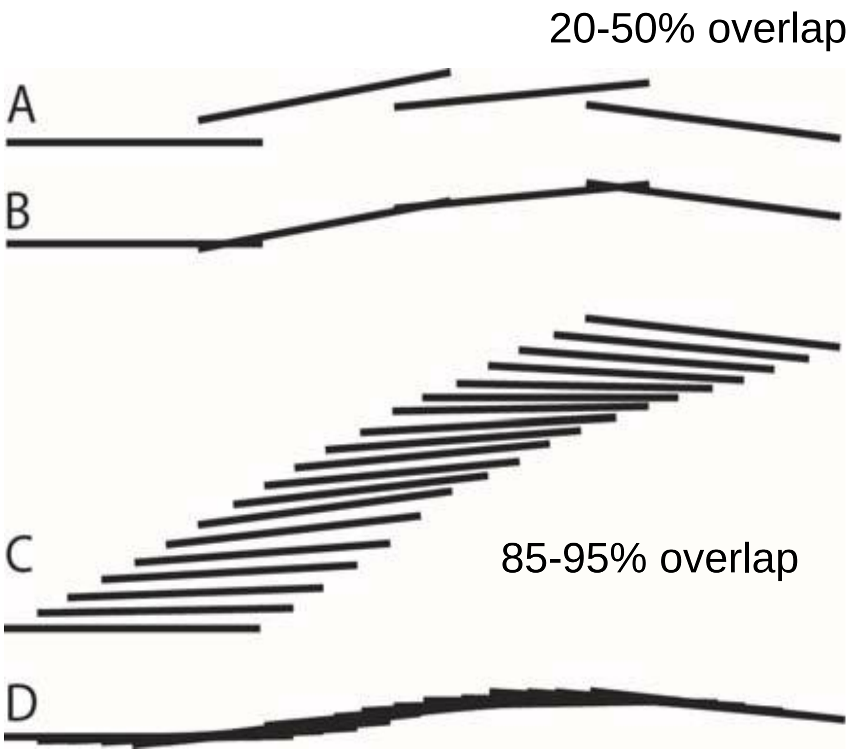
0.3 nm PV

Step Based ITF

NanoCam ITF



Fine Motion Stitching



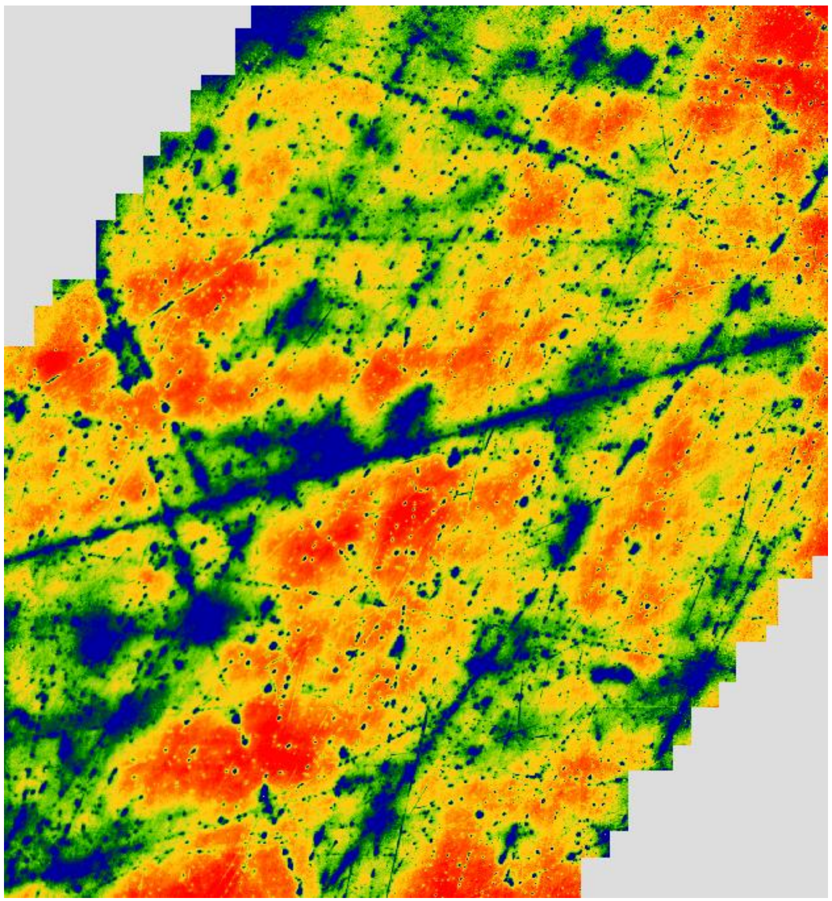
- Multiple frame data averaging
- Minimal displacement between measurements allowing greater precision in tracking frame to frame displacement.
- Scanning can be with a continuous vice start/stop motion; improving overall speed and simplifying the measurement procedure.
- Large overlap regions allow better determination of local slope and offset resulting in a more accurate composite measurement.

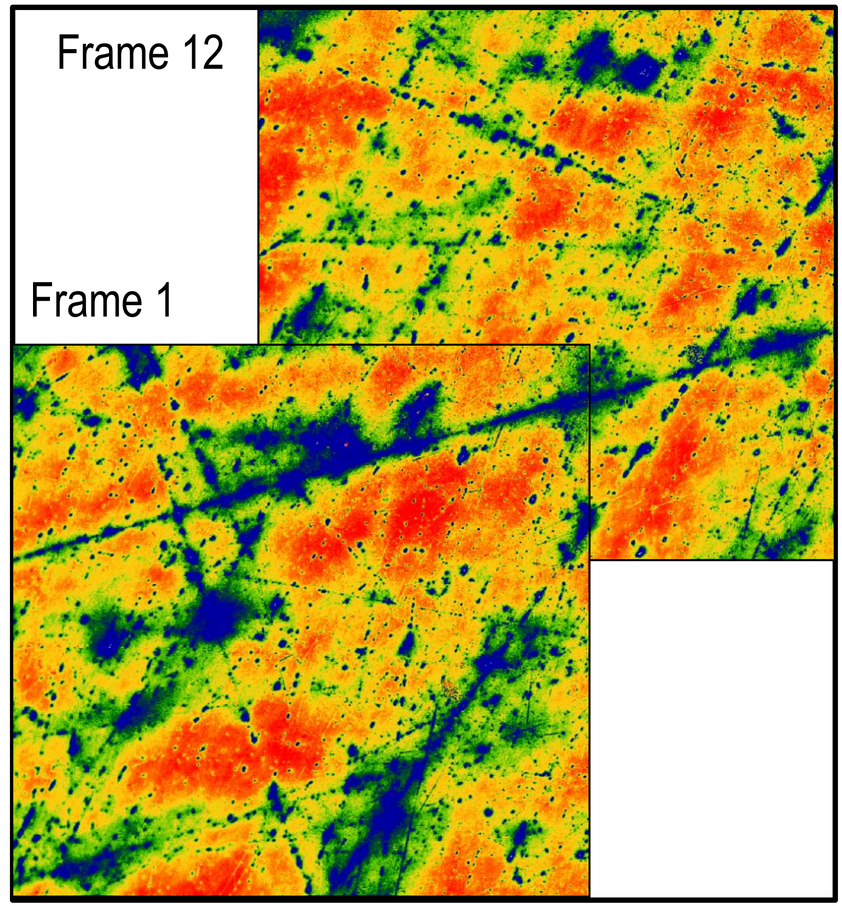
Correlation position sensing

- Fine motion scanning allows robust displacement tracking through use of image correlation
- Use image correlation to track movement
  1. 1 pixel accuracy
  2. Better accuracy if you fit the correlation map
- Stitch together and average based on correlation shifts.
- Caveats
  - Sufficient surface structure required for good correlation
  - Image rotation would not be tracked.

Fine motion stitching

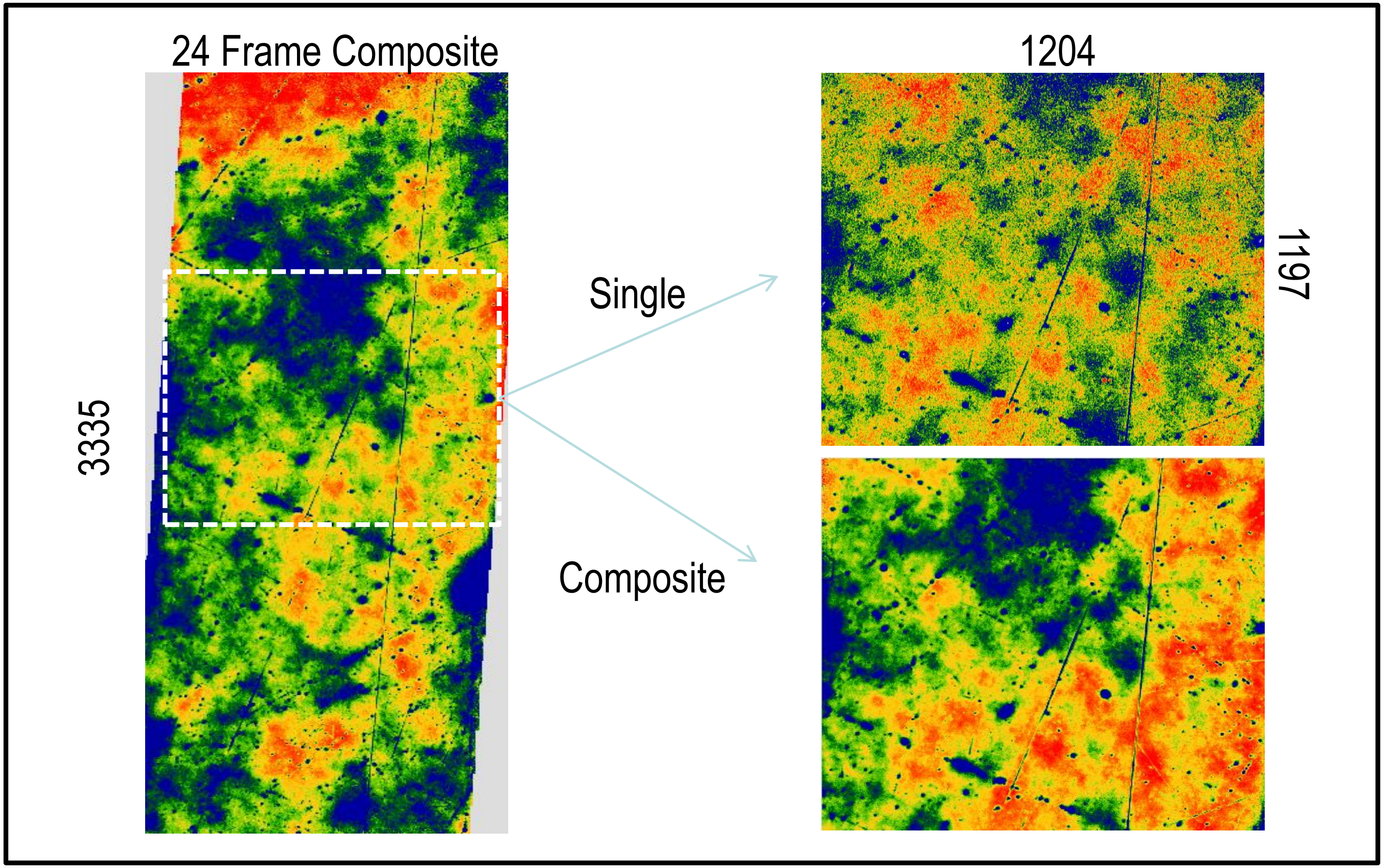
(10X, correlation tracked displacement)



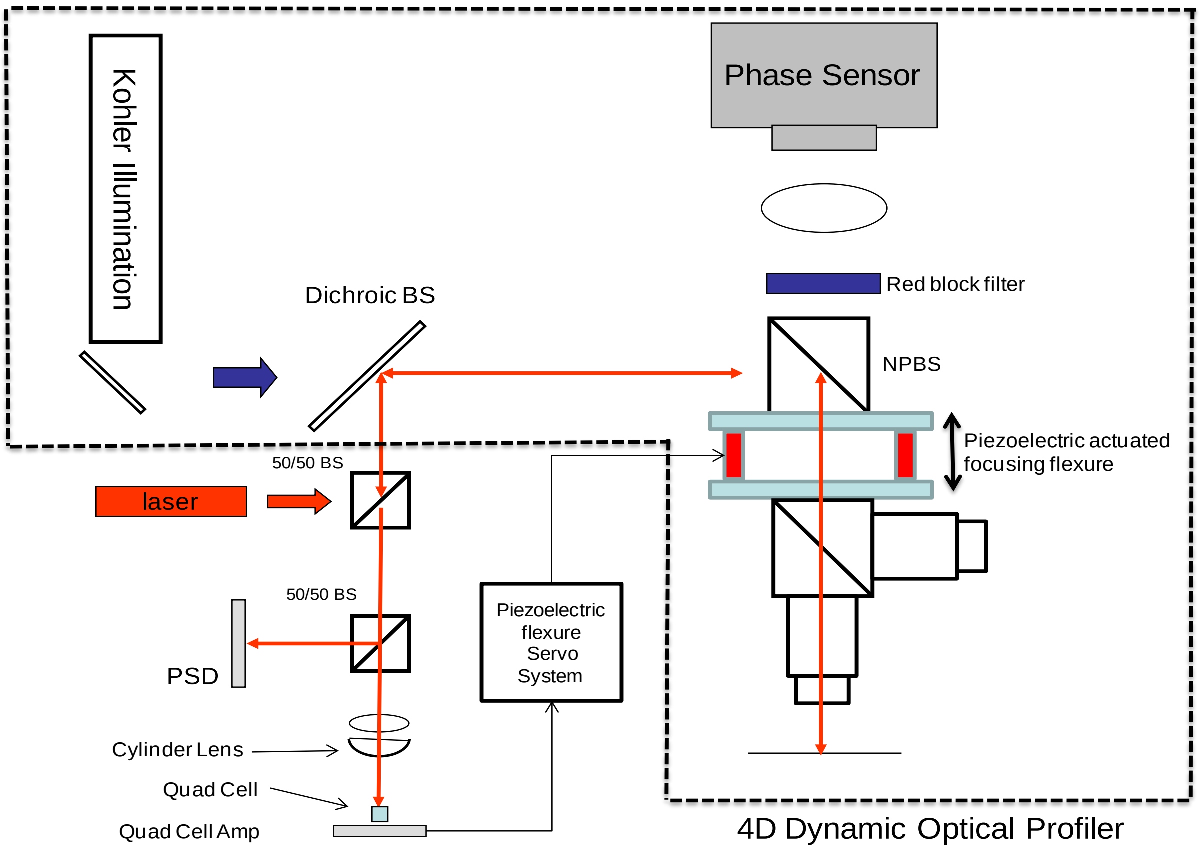


Averaging for noise reduction

(10X, correlation tracked displacement)



Auto Focus and Tip/Tilt Sensor



4D Dynamic Optical Profiler

<u>Focus Sensor</u>

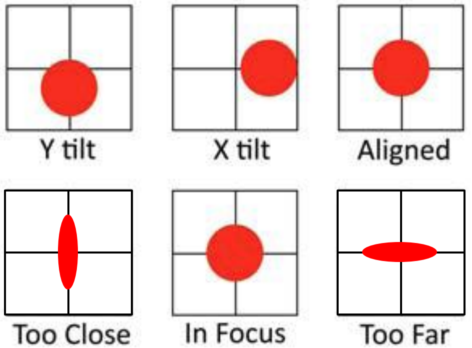
Range: +/- 100 um

Sensitivity: +/- .2 um

<u>Tilt Sensor</u>

Range: +/- 10 deg

Sensitivity: +/- 0.2 wv



Future Plans / Milestones

- Near Term
  1. ITF measurements based on PRG technique
  2. Complete design and evaluation of auto focus and alignment mechanism
  3. Refine fine motion stitching algorithms and continue evaluation
- Mid Term
  1. Design and integrate auto focus and alignment sensor
  2. Fully integrated stitching solution.
  3. Evaluate field study results for design improvements

Thank You