Optical and tactile methods for measuring miniature high aspect ratio structures

2nd Target Fabrication Workshop

October 2008

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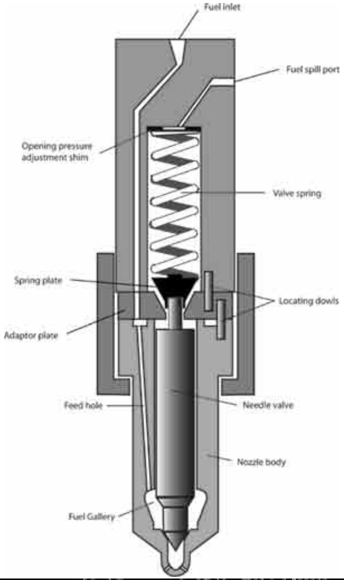
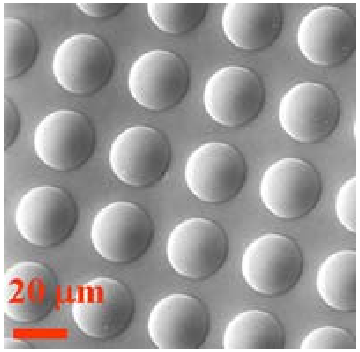
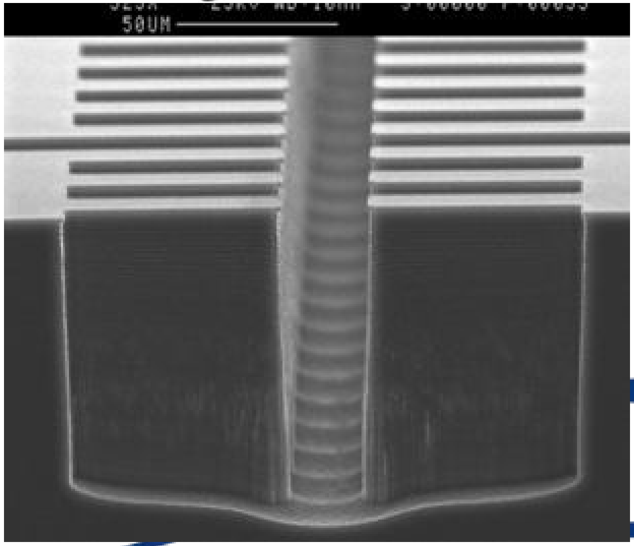
National Physical Laboratory

“True-3D” micro-metrology

- Modern manufacturing involves 3D integration of 3D micro-parts
- Have you ever taken apart your mobile telephone?
- Small optics, micro-mirrors
- Micro-fluidic components, lab-on-a-chip
- Medical devices
- MEMS structures
- Ink-jet/diesel injectors
- Small parts with ever-decreasing tolerances







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Micro-coordinate metrology

- As part of the DTI-funded CEMMNT project, NPL has procured a Zeiss F25 micro-CMM
- Range 100 mm x 100 mm x 100 mm
- Existing mechanical probes down to 0.3 mm diameter – need smaller
- Accuracy stated as 250 nm but this is conservative
- Probe resolution 10 nm
- Probing force a few μN
- Also incorporates an optical “vision” probe

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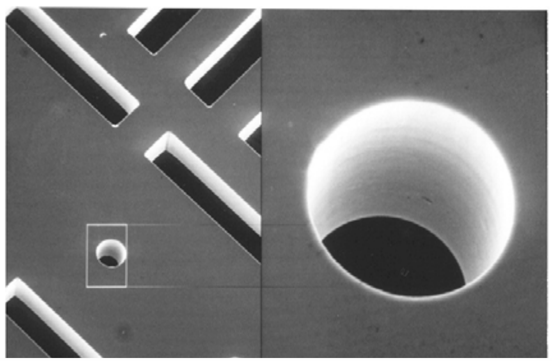
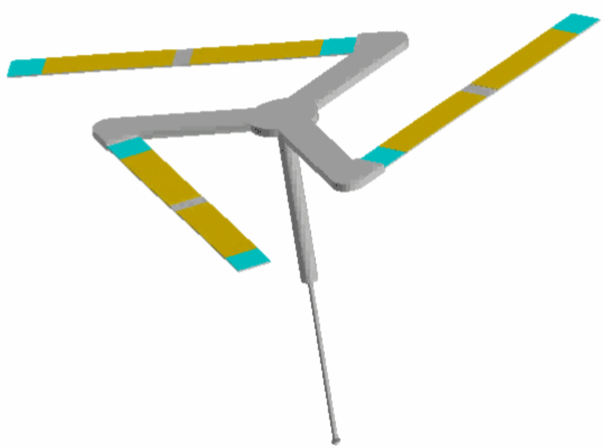
So why not just shrink the probe?

- The laws of physics are not simply scaleable, there are jumps
- Aspect ratio becomes a problem
- Surface forces dominate over gravitational (stiction)
- Basically, things get too floppy

Micro-probe for micro-CMM

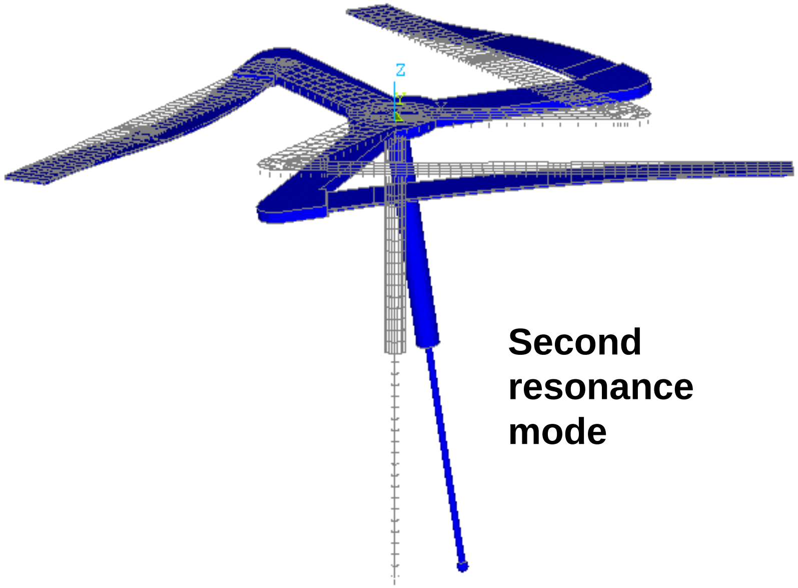




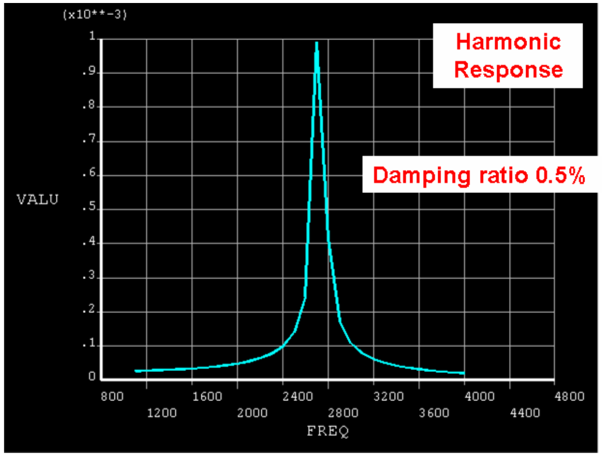
- Developing vibrating micro-CMM probe to interface with Zeiss F25 micro-CMM (1 mm length, $\phi < 50\ \mu m$)
- F25 also has a vision probe – essential for location on part
- Collaboration with Cardiff, Greenwich, Cranfield, Cambridge, Nottingham and Taipei
- Applying for patent – licence to Zeiss

Modelling and Simulation

- Modal and harmonic analysis
  - Resonance condition (short circuit)
- Helped to understand
  - Resonance frequencies
  - Effect of flexure material on resonance (nickel, silicon and glassy carbon)
  - Behaviour near resonance frequency



Second resonance mode



In-plane displacement of the tip vs. frequency

Silicon Flexures

SET	FREQ f (KHz)
1	1.841
2	3.368
3	3.368
4	20.287
5	20.287
6	20.291
7	27.064
8	27.064

Glassy Carbon Flexures

SET	FREQ f (KHz)
1	1.515
2	2.727
3	2.728
4	14.968
5	14.968
6	15.107
7	18.006
8	18.006

Nickel Flexures

SET	FREQ f (KHz)
1	1.142
2	2.113
3	2.113
4	14.186
5	14.187
6	14.243
7	17.561
8	17.561

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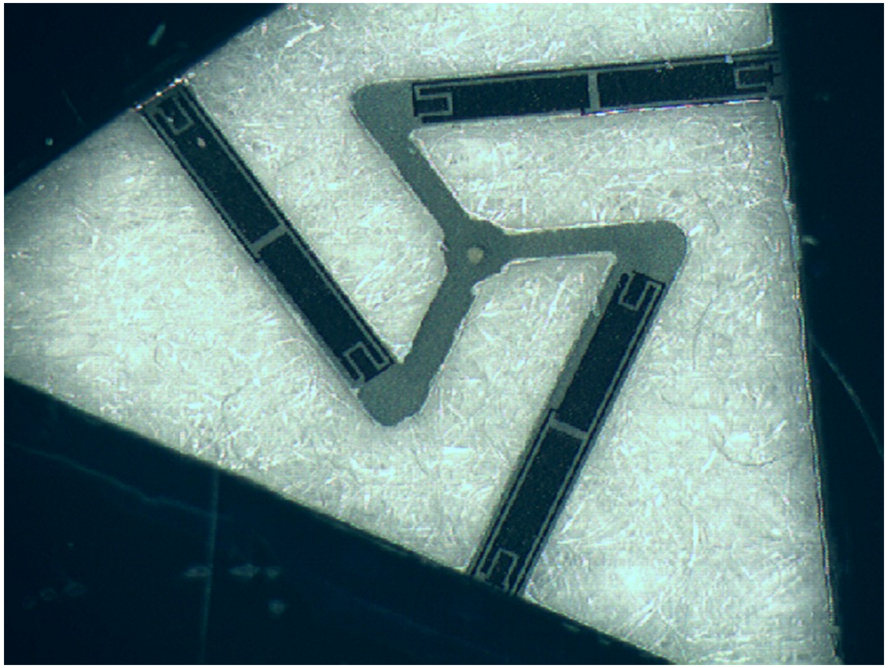
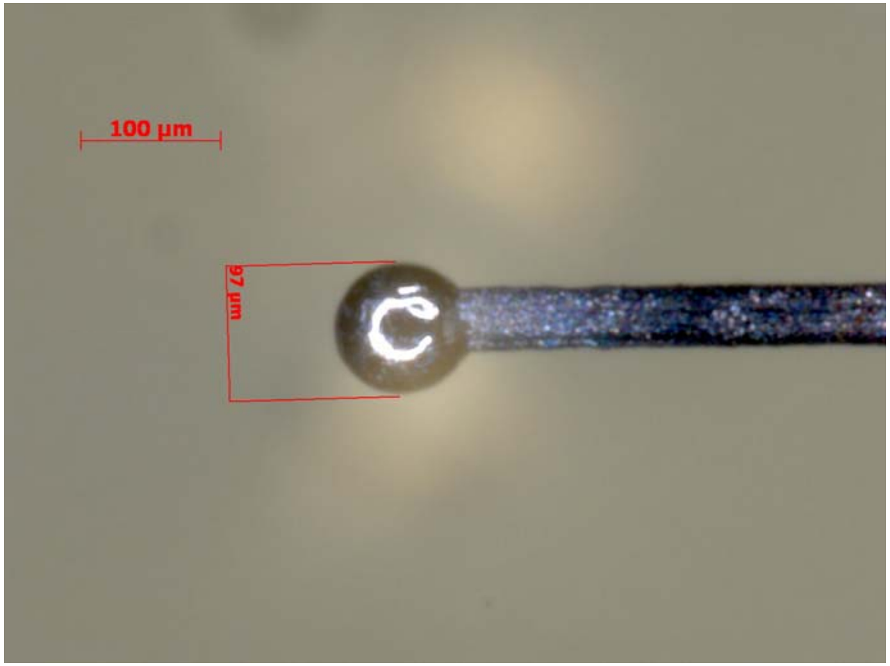
Prototype flexure manufacture

- Cranfield University
- PZT thin film layers on nickel using a silicon sacrificial substrate (removed using DRIE)
- Problems with glassy carbon
- Flexure now need electrical and mechanical testing and comparison with model

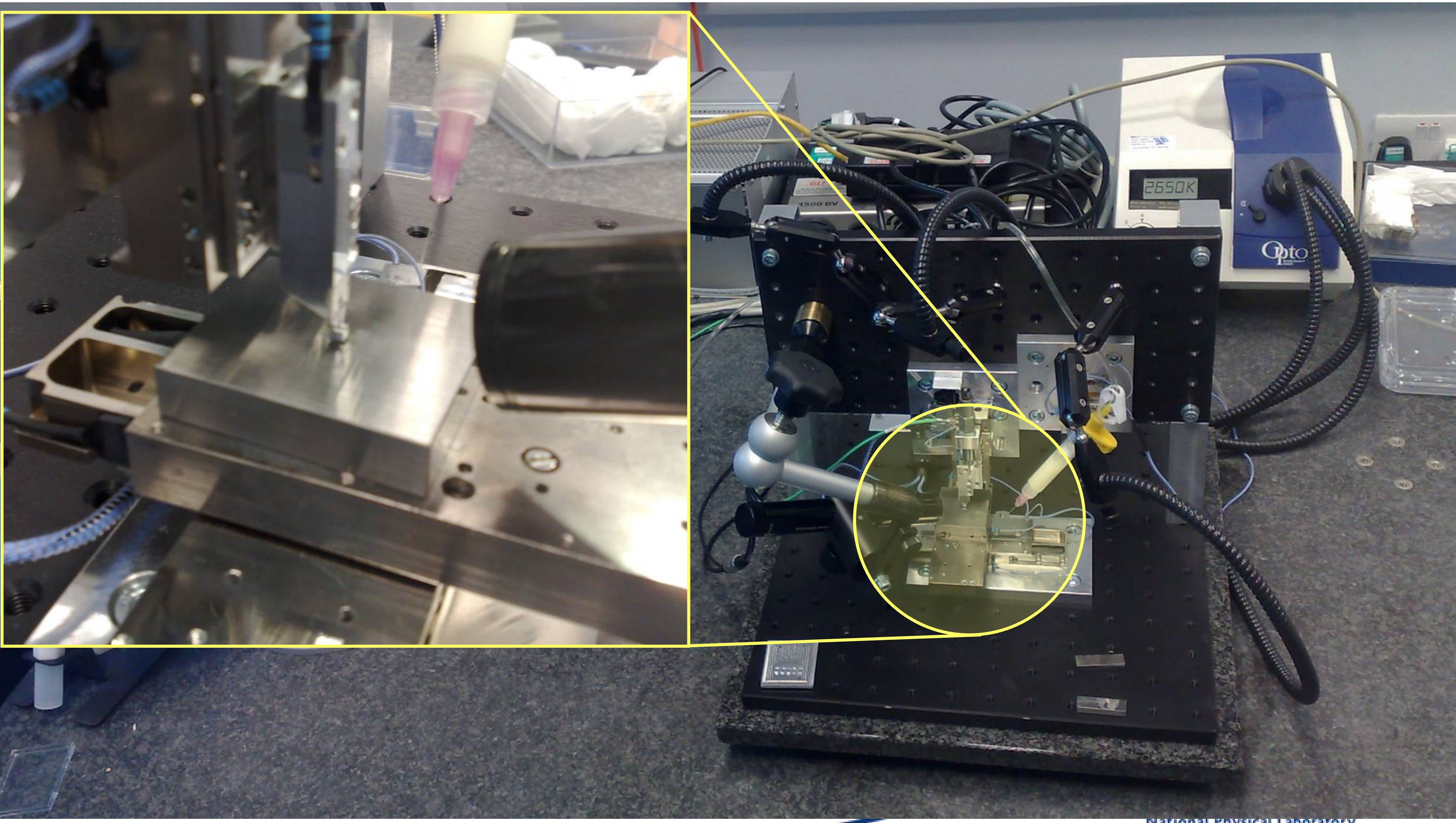


Prototype probe manufacture

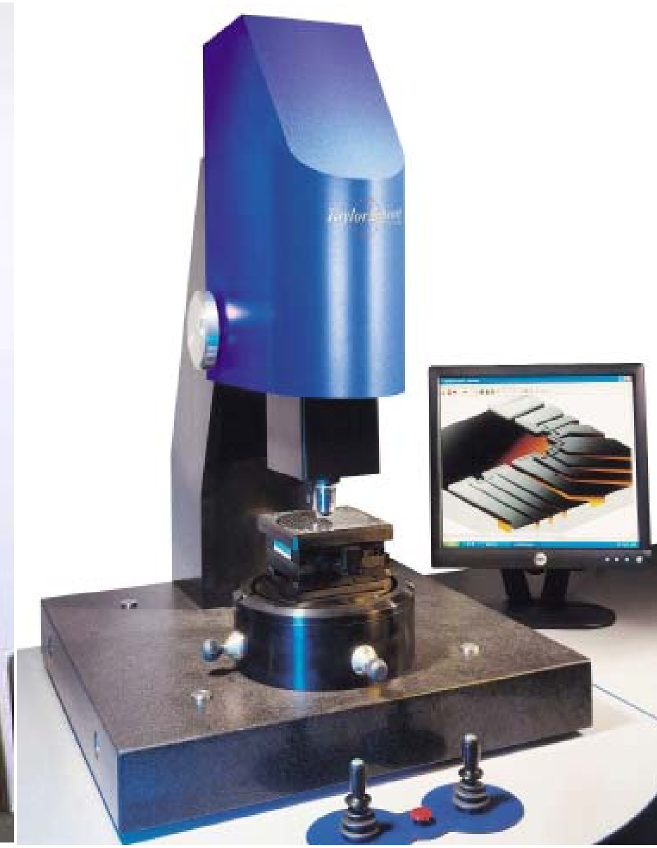


- Ball on stem manufactured using micro-EDM
- Ball direct machining led to rough and cracked end
- Attempting laser and etch methods to clean
- Ball also made by a melting and surface tension method

The microassembly system - Nottingham



Commercial SWLI Instruments



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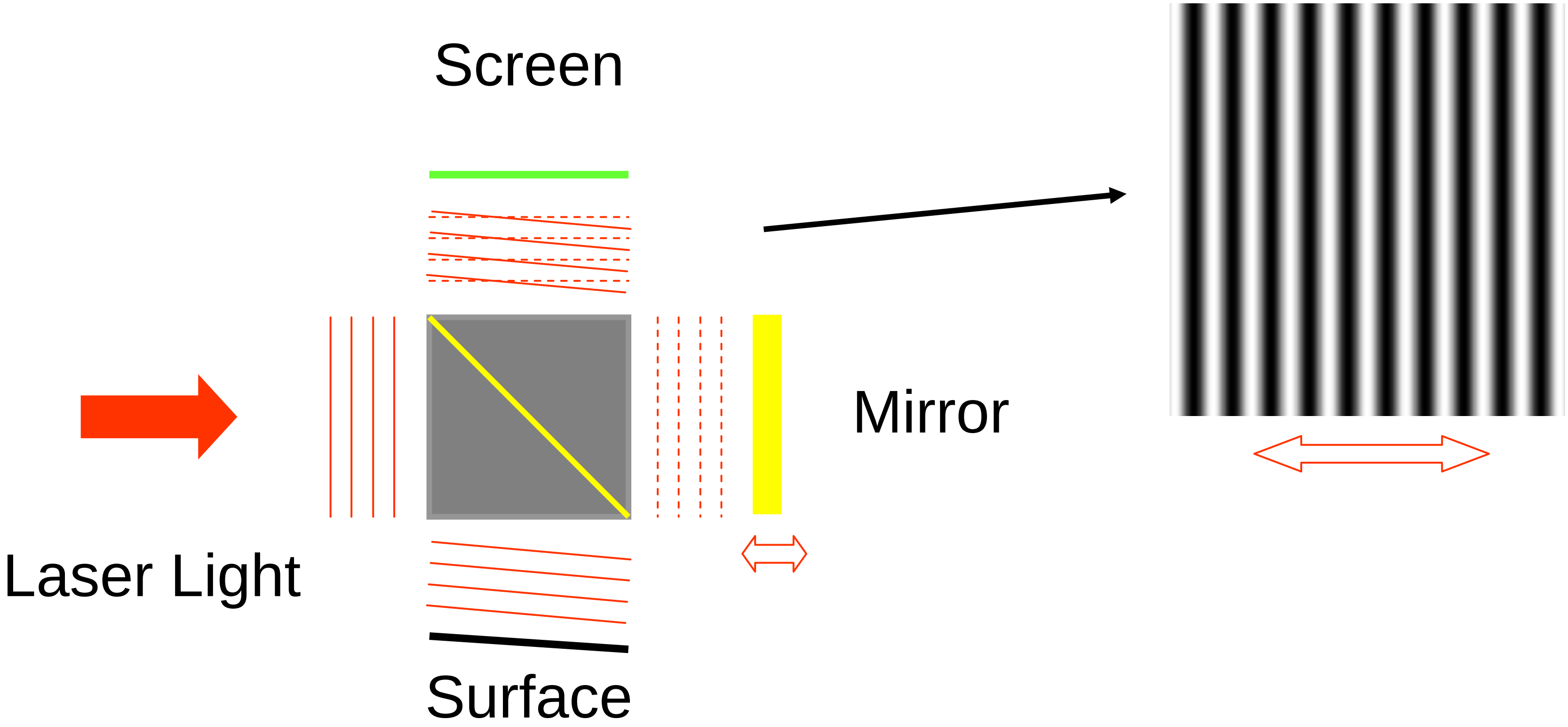
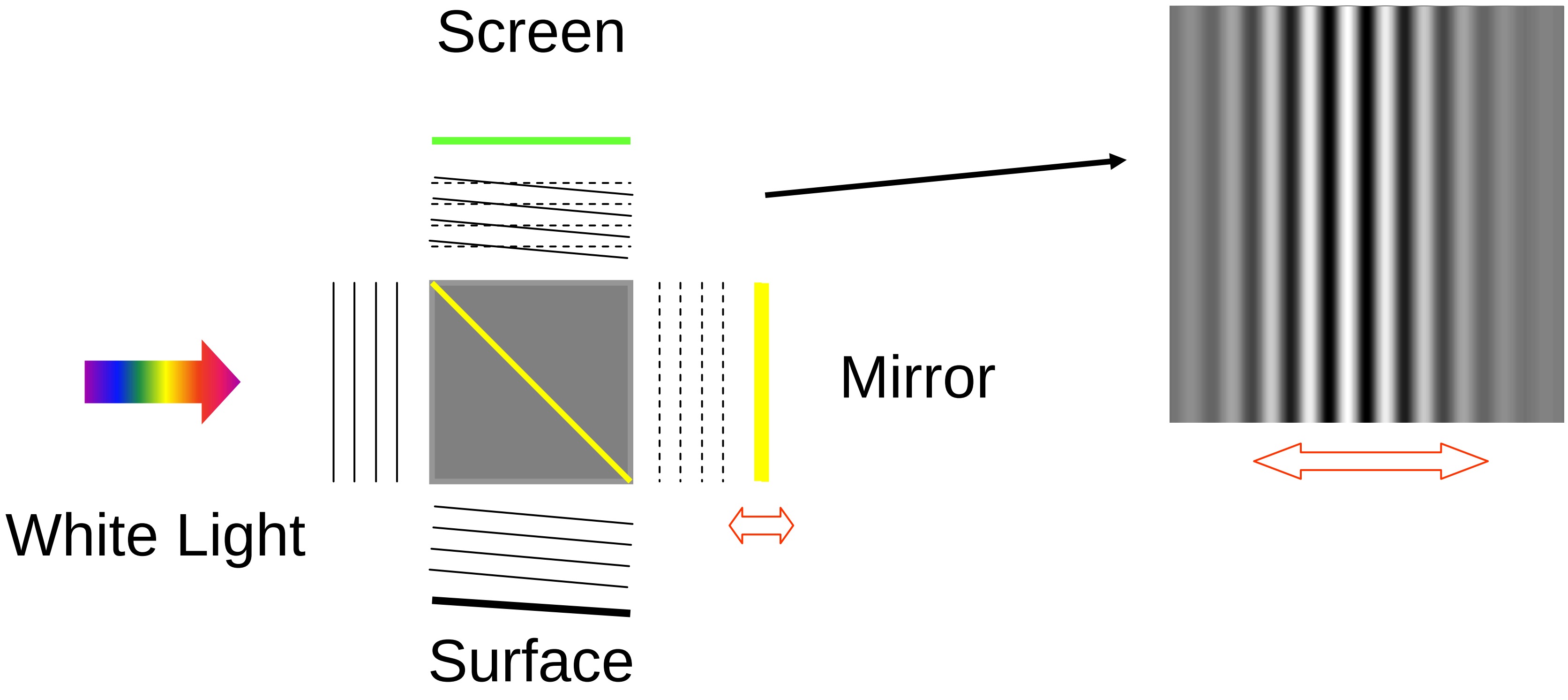
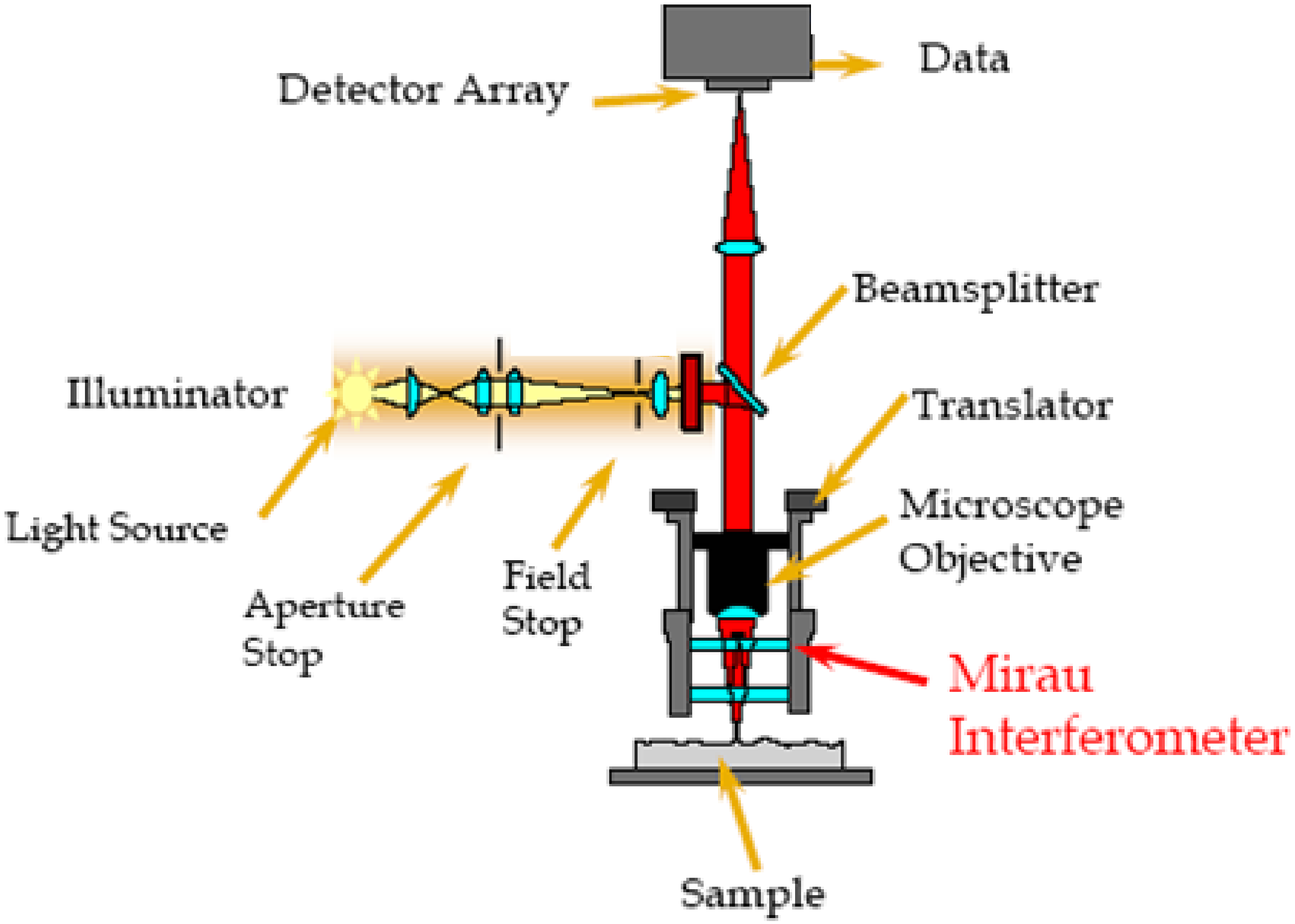
Michelson Interferometer – Laser Illumination



Michelson Interferometer – White Light Illumination

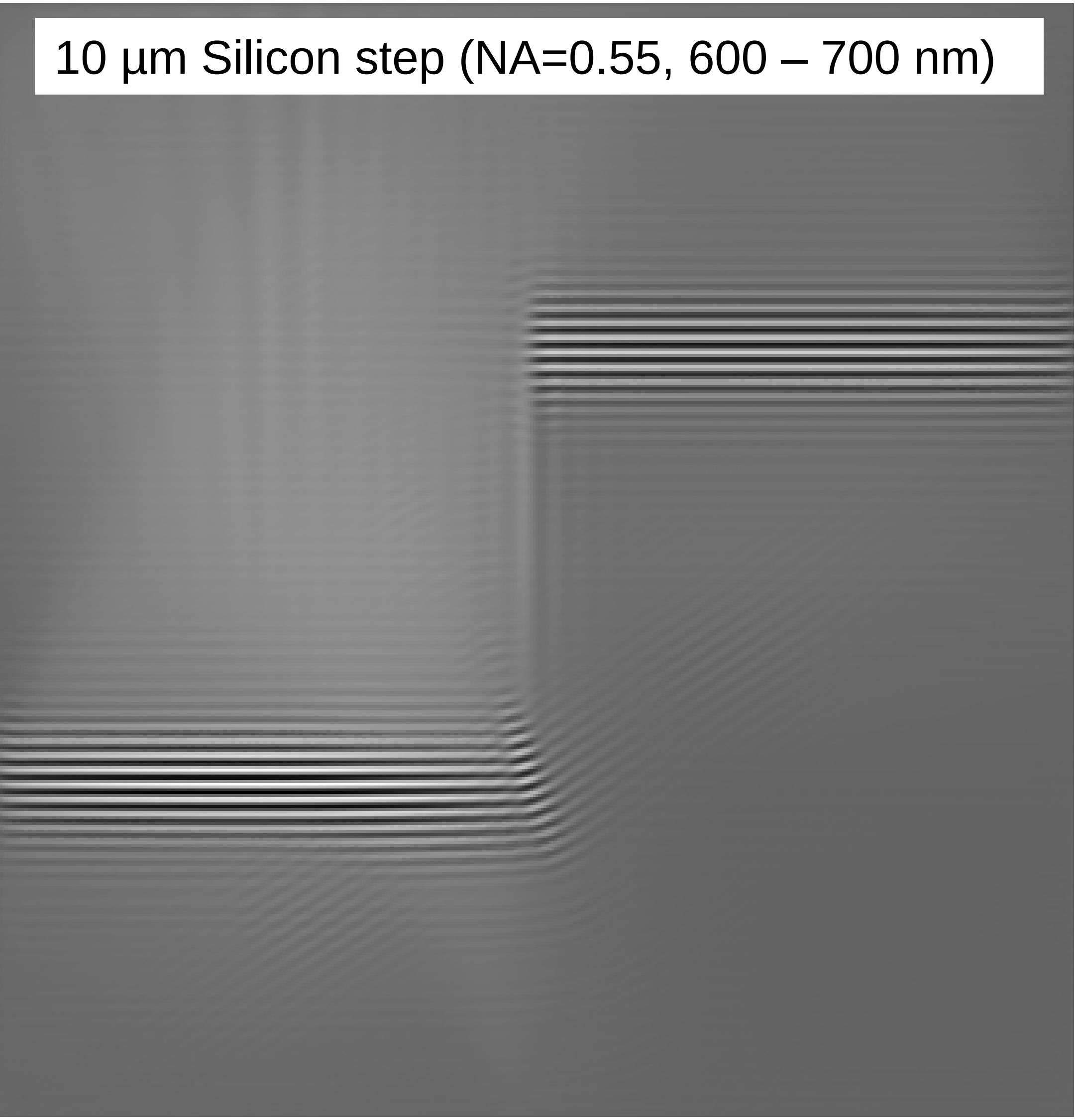


Schematic


Detector Array
Data
Beamsplitter
Illuminator
Translator
Light Source
Microscope
Objective
Aperture
Stop
Field
Stop
Mirau
Interferometer
Sample

Step Interferogram

10 µm Silicon step (NA=0.55, 600 – 700 nm)



The information present in the interferogram is related to the step height by estimating the position of peak visibility (called vertical scanning interferometry (VSI) mode), and/or the phase of the interference fringes (called phase shifting inteferometry (PSI) mode).

Some SWLI Limitations

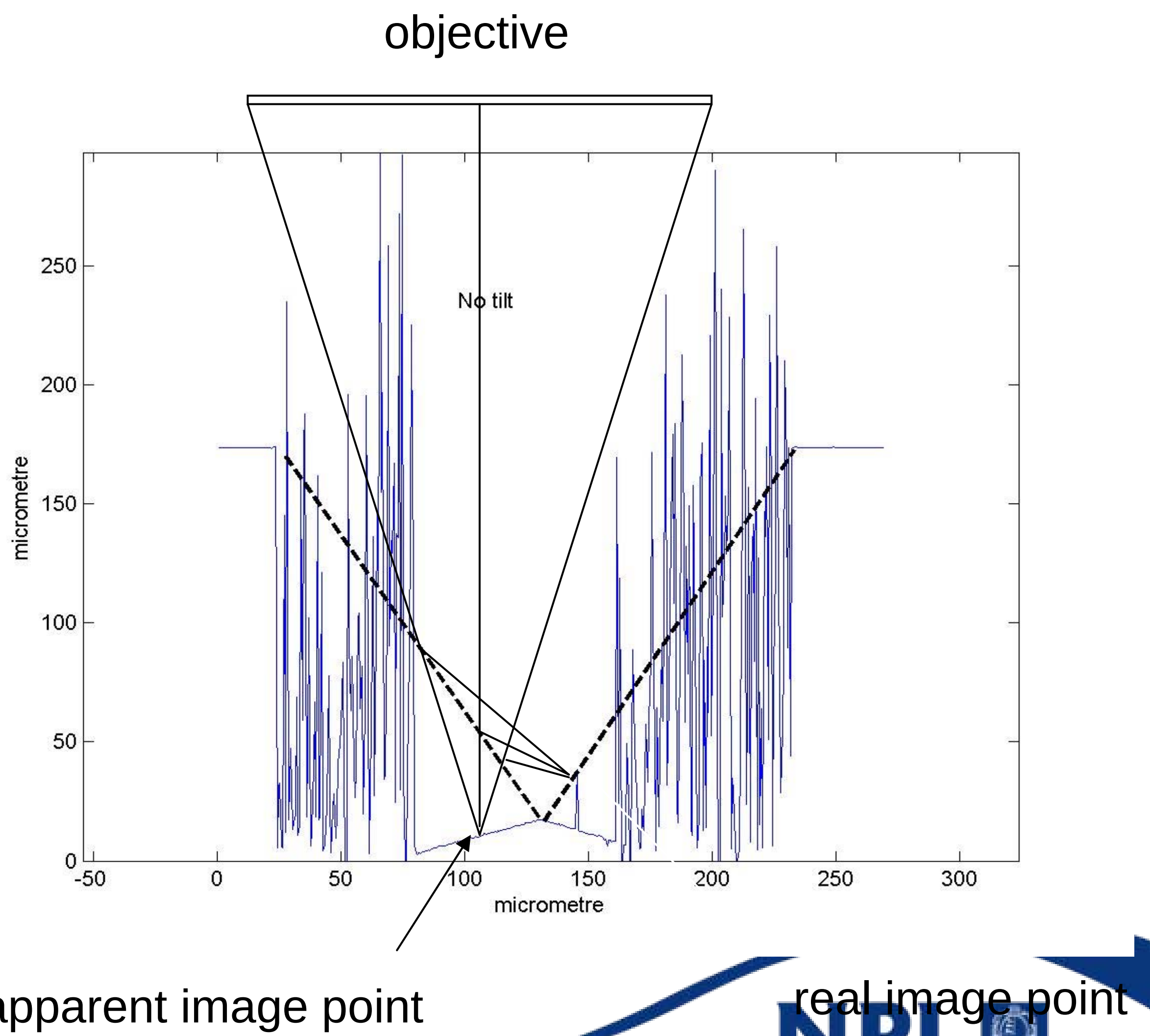
- Edge Artefacts – The Bat Wing Effect
- Ghost Steps – Dispersion Effects
- Material Effects
- Multiple Scattering / Surface Roughness Measurement

“Surface Measurement Errors using Commercial Scanning White Light Interferometers” F Gao, R K Leach, J Petzing and J M Coupland *Meas. Sci. Technol.* **19** (2008)

Optical limitations – vee-groove example

A basic ray analysis shows this type of error is due to multiple reflection

Note the error is approximately 100 μm here!



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Problems Summary

- SWLI errors can be classified as:
  - Instrument related errors
    - Dispersion
    - Signal processing
  - Surface related errors
    - Refractive index changes
    - E/M surface interactions

Q. Can anything be done?

A. Yes, but we need to think a bit more about E/M surface interactions

E/M Modelling

- The propagation of E/M waves in non-homogenous media can be solved using:
  - Finite Element Methods (FEM)
  - Boundary Element Methods (BEM)
  - Iterative scattering models (Born Iterative Method, Distorted Born Iterative Method)

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Inverse Problem

So we know we can produce interferograms that show the surface related problems of WLI using FEM/BEM to solve *the forward problem.*

Q. Can we calculate the surface accurately from one or more interferograms?

This is *the inverse problem*. Mathematically it is the solution that minimises an error function such as,

$$\text{Error} = \sum \left(E_S^{m} - E_S^{calc.} \right)^2$$

Measured scattered field

Calculated scattered field

A. Sometimes!

Conjugate Gradient Method

- Optimisation in inverse problems is often implemented using the Conjugate Gradient Method (CGM)
- Since the first iteration of CGM optimisation is a step in the direction of a linearisation of the forward problem it is also closely related to the SWLI fringe pattern!

J Lobera and J M Coupland "Optical Diffraction Tomography in Fluid Velocimetry: The use of A-priori Information" To be published in Measurement Science and Technology 2008

- In essence optimisation is therefore the process of:
  1. Taking a SWLI image
  2. Finding "good data"
  3. Building a model
  4. Calculating new image by back-propagation of SWLI measurements through model

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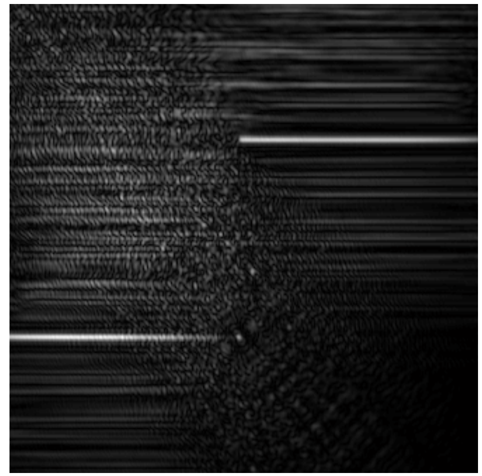
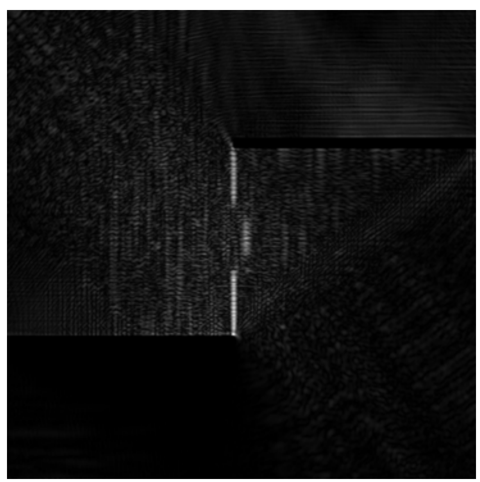
Example: The Profile of A Vertical Wall (2 Iterations)

Object: 15 μm step with a 5 μm x 1 μm groove. Illumination from the top.

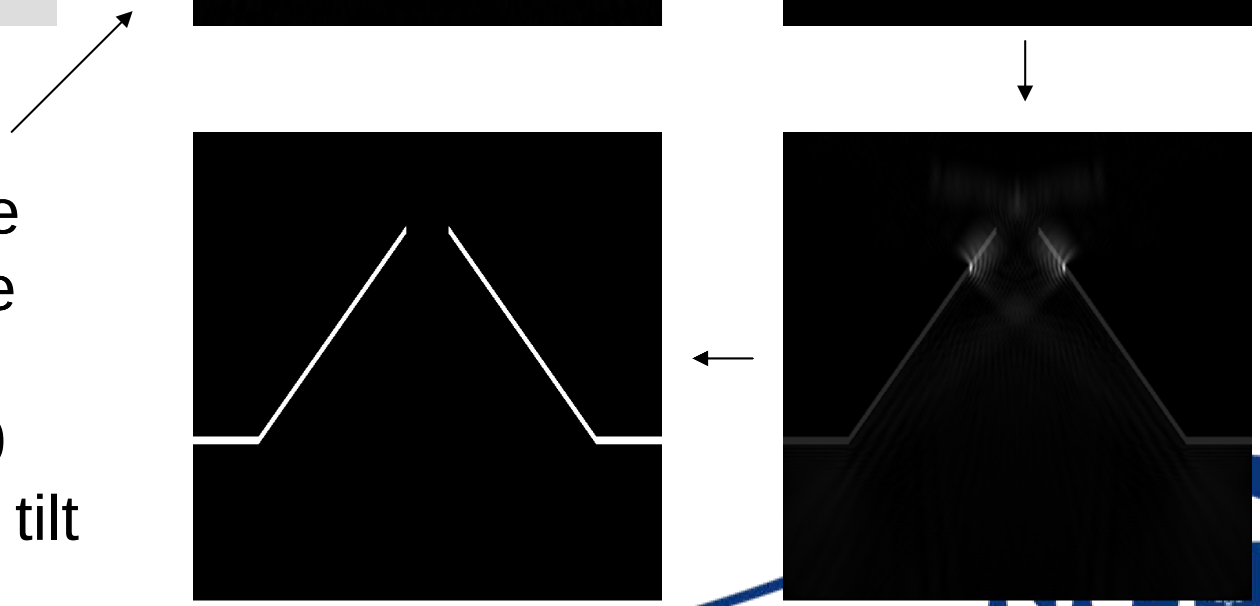


SWLI results (abs. value): top and bottom surfaces are found.

New object calculated from SWLI data using updated model shows the profile of the “vertical wall”

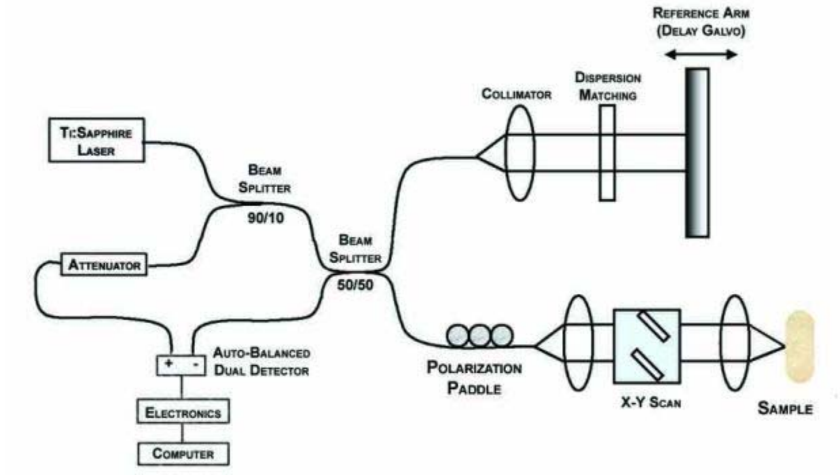


Example V-Grooves

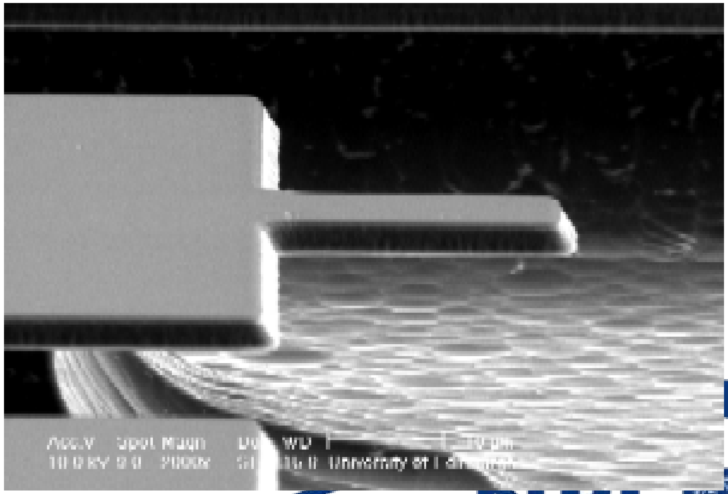


This needs to be large NA it is the superposition of images at -30, 0 and +30 degree tilt

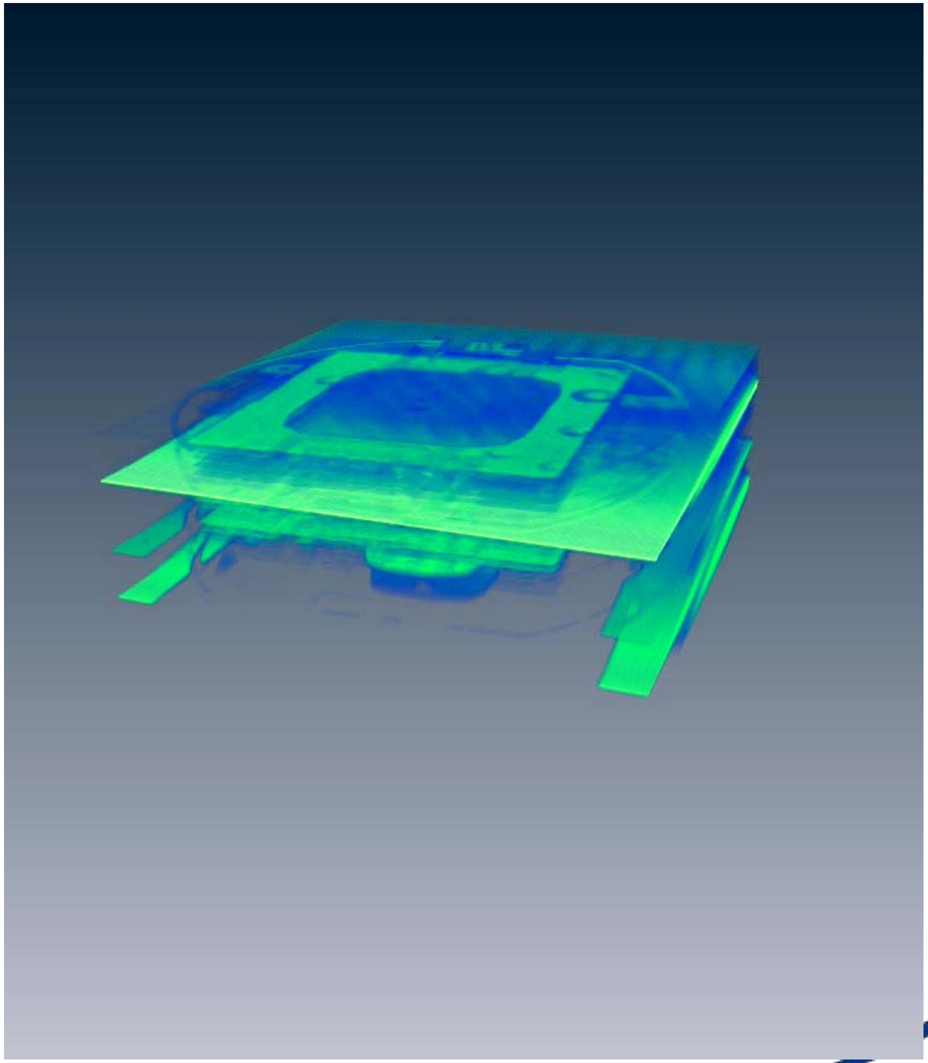
Measurement of absolute thickness of MEMS structures



- Joint Industry Project to develop tomographic methods for thickness measurement
- HAR measurement also considered
- Absolute thickness measurement for wafers, membranes, cantilevers, *etc.* using IR-OCT and IR-confocal
- Collaboration with Druck, QinetiQ, Olympus and Michelson Diagnostics



IR-OCT for MEMS thickness



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Conclusions

- Conventional surface and CMM measurements struggle to measure complex 3D, high aspect ratio structures
- But, new developments and new interpretations of “errors” can be used to increase versatility
- Huge problem is measuring the sphericity and surface quality of small spheres
- Can also apply tomography methods for internal structure – see AWE presentation