Metrology challenges for highly parallel micro-manufacture

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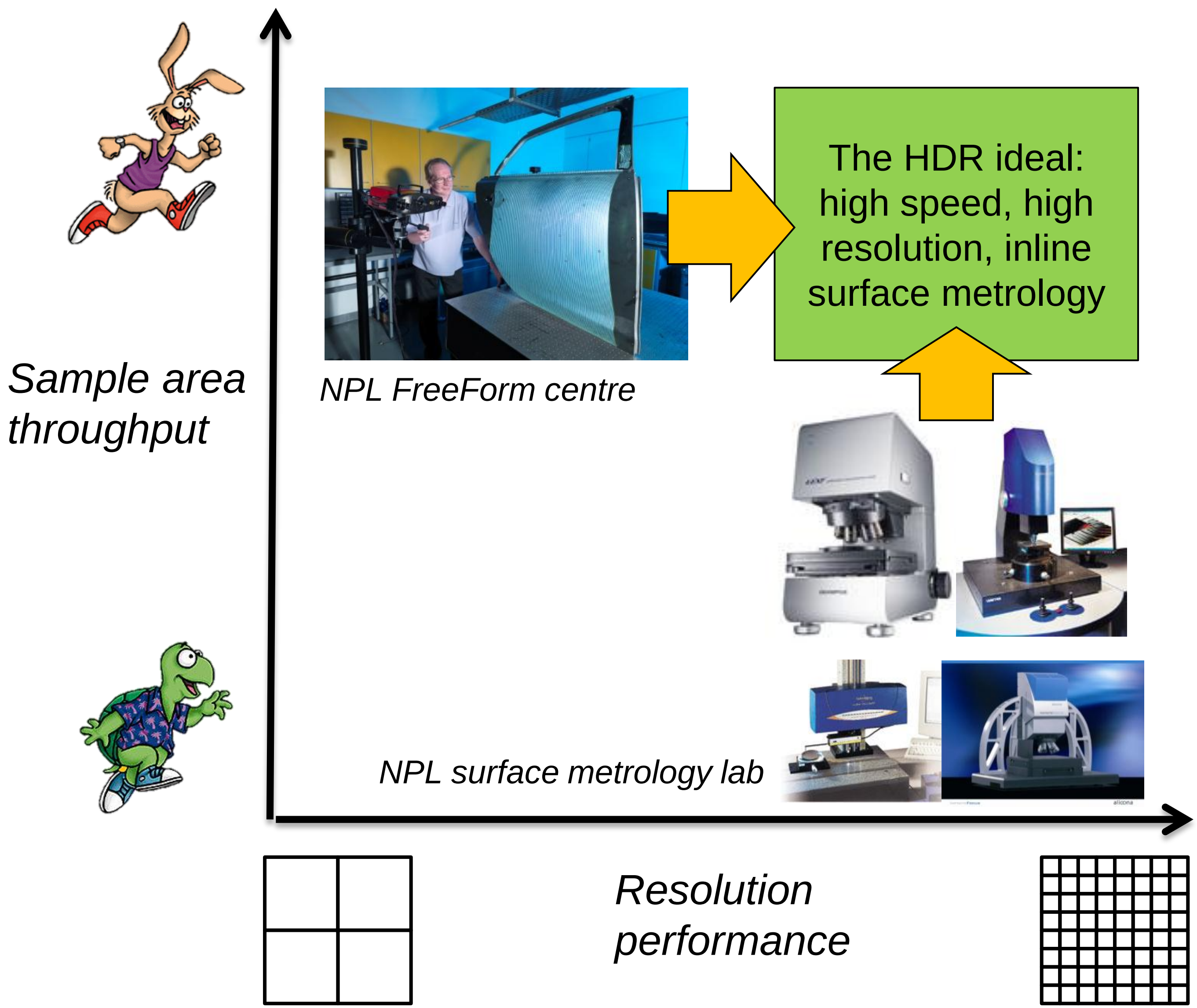
Content of talk

National Physical Laboratory

- Introduction to HDR metrology
- Point sensors
- Areal sensors
- Super-resolution
- HDR conclusions
- Other areas of interest

An illustrative example

What is HDR surface metrology?



What is HDR surface metrology?

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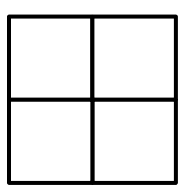
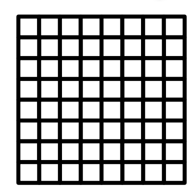
Sample area throughput

HDR ideal:
Fast, hi-res,
inline metrology

- Photovoltaics
- Micro-optics
- Printed/plastic electronics
- Coated paperboard
- Glass manufacture
- …



Resolution performance



What is HDR surface metrology?

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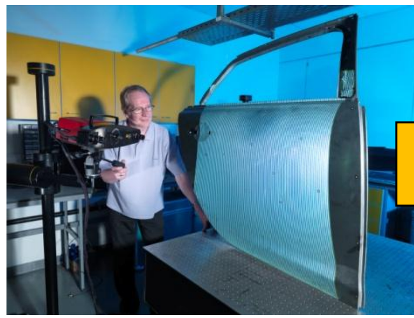
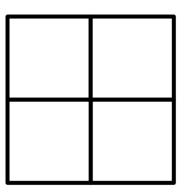
Sample area throughput



NPL FreeForm centre

- ✓ high throughput
- ✓ complete image
- ✓ proven inline metrology
- ✗ resolution for MNT
- ✗ surface tolerance for MNT



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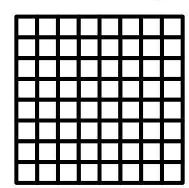


What is HDR surface metrology?

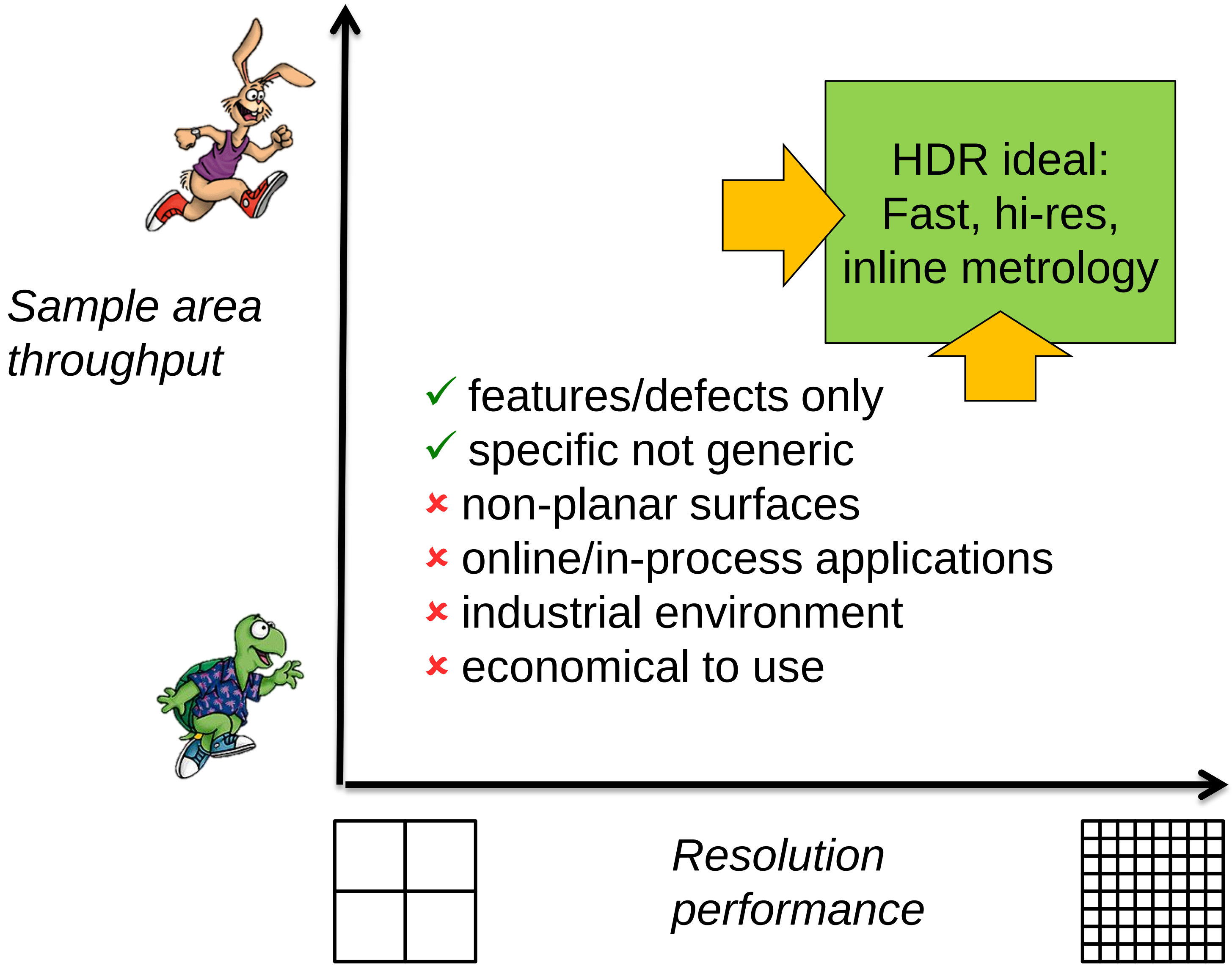
- ✓ complete image
- ✓ resolution for MNT
- ✓ surface tolerance for MNT
- × inline metrology (for now)
- × very low throughput

Sample area throughput

NPL surface metrology lab

Resolution performance

What is HDR surface metrology?



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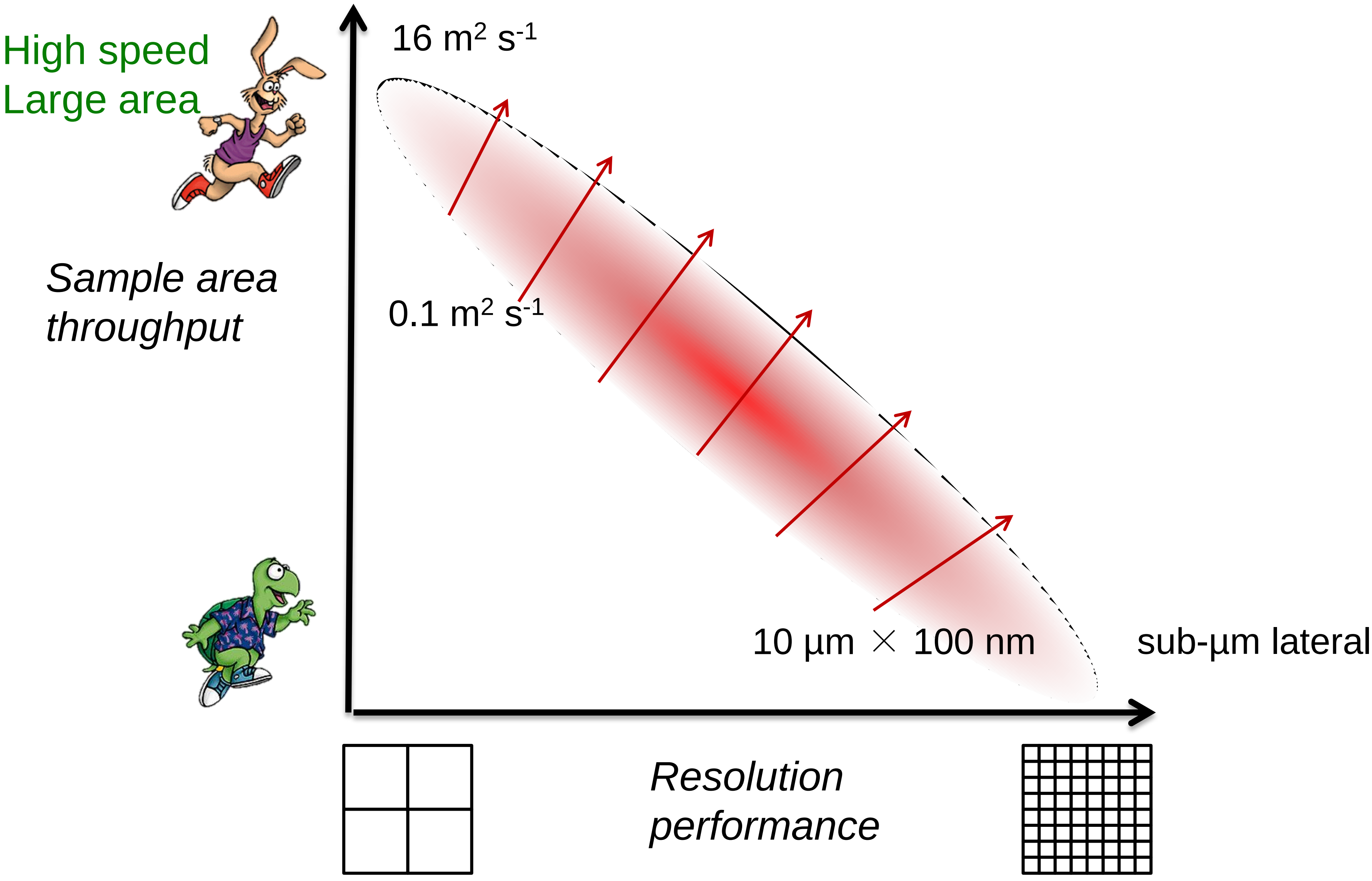

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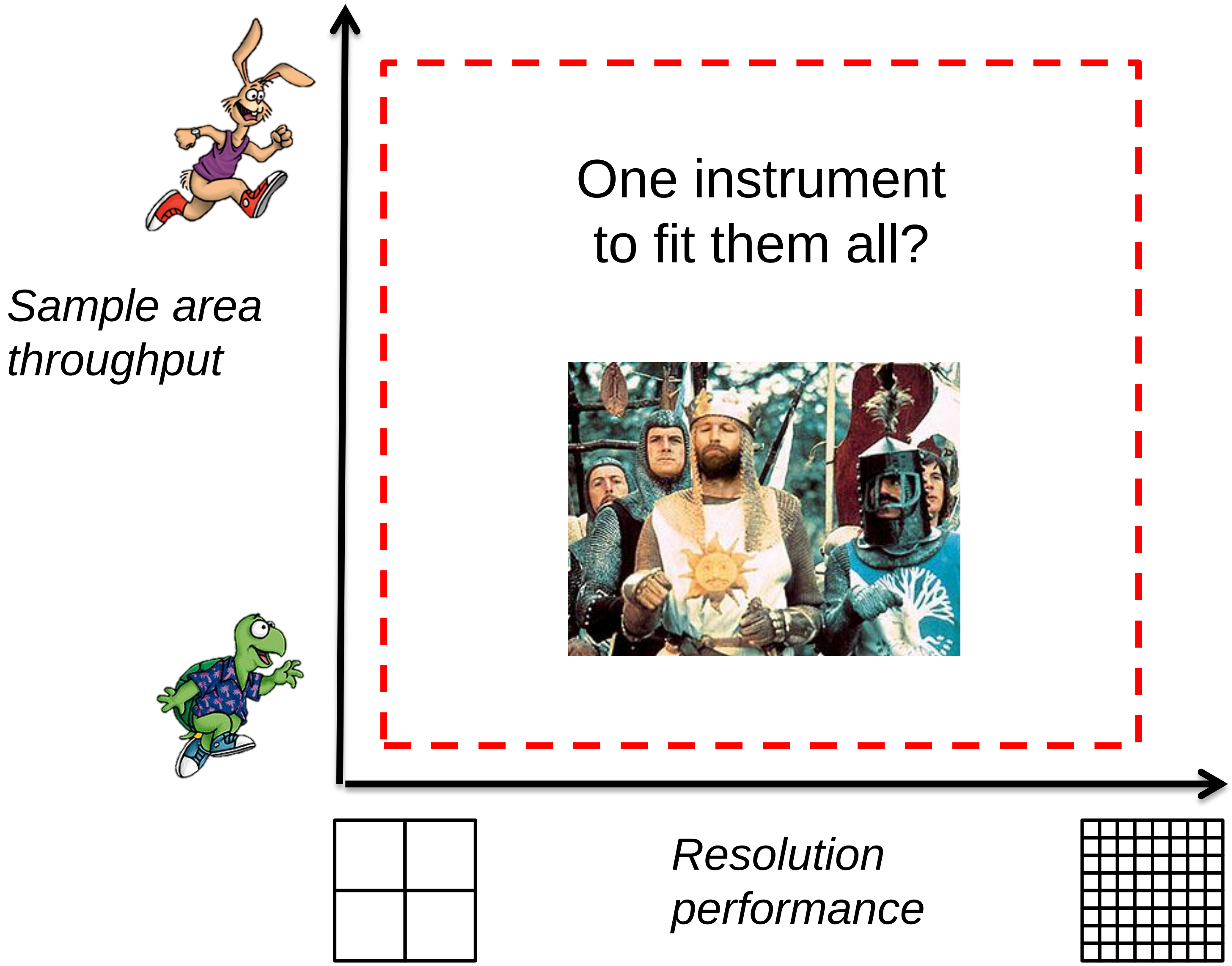
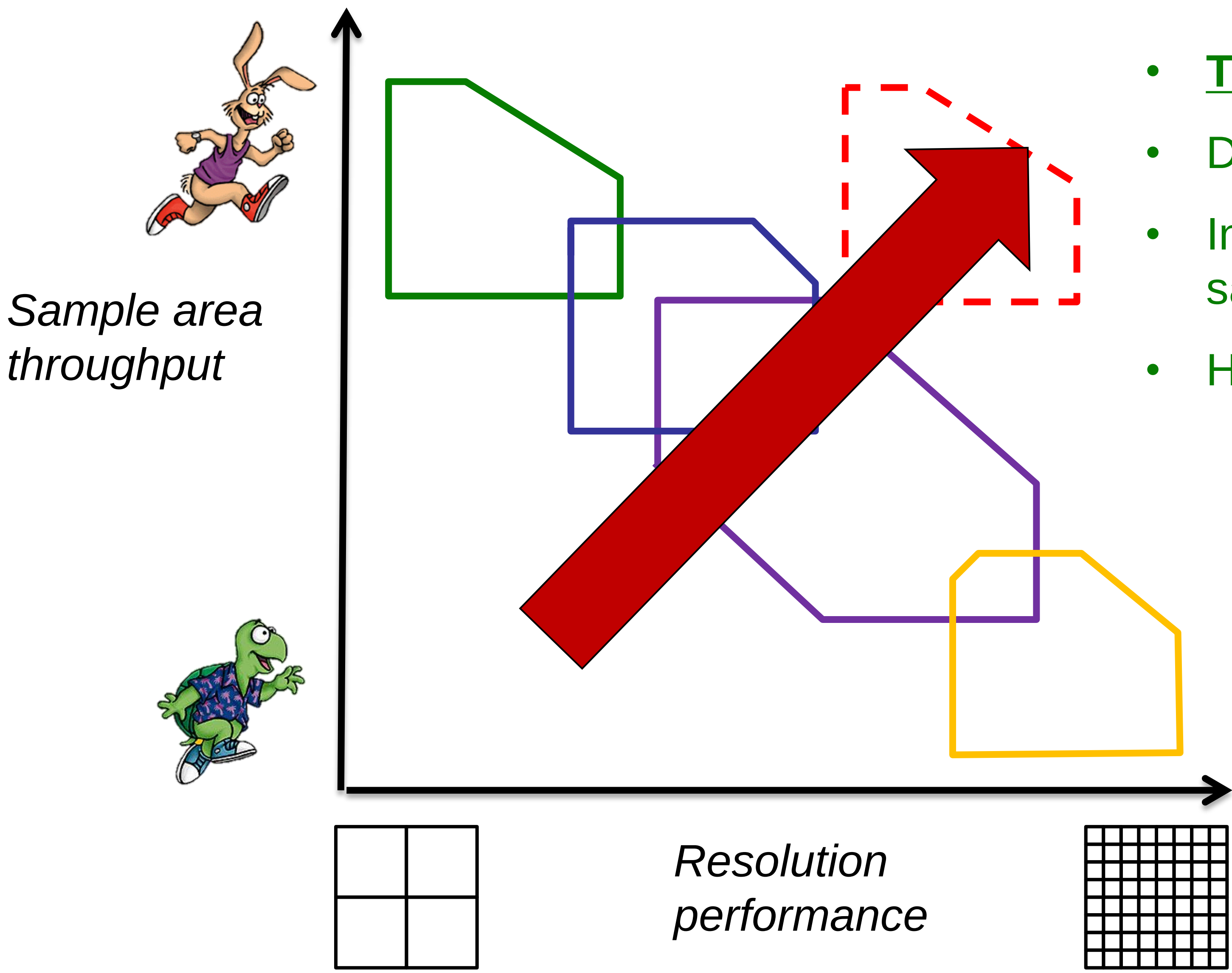
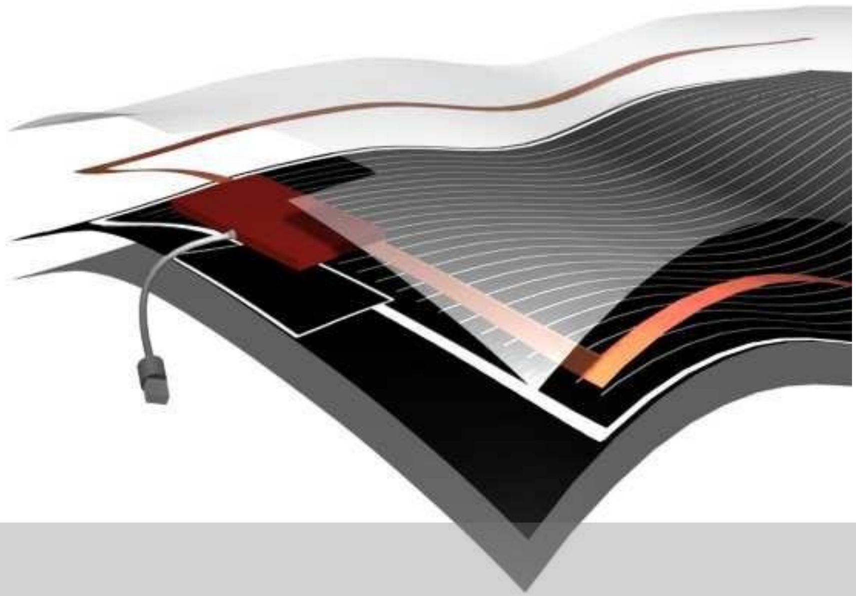


What is HDR surface metrology?



- **<u>Toolbox</u>**
- Data fusion
- Intelligent sampling
- Hybrid sensors

www.nanomend.eu



Flexible Solar modules

Image courtesy of Flisom

The inside of food and liquid packaging

Image courtesy of Stora Enso

Detection – cleaning – repair

The NANOMend (formerly NANOCleaR) project has received funding from the European Community’s Seventh Framework Program (FP7/2007-2013) under Grant Agreement No. 280581

Metrology challenges

- Increase the speed of high-resolution sensors
  → overcome conflict between speed and resolution.
- Overcome the limit on the smallest detectable defect
  → resolution enhancement for fast sensors
- Prioritise defects to simplify inspection and measurement
- Find better ways to apply and test protective thin films themselves

SEVENTH FRAMEWORK PROGRAMME

NANOMEND
METROLOGY FOR ENHANCED NANO-SCALE DETECTION, CLEANING AND REPAIR

Recent progress in the consortium*

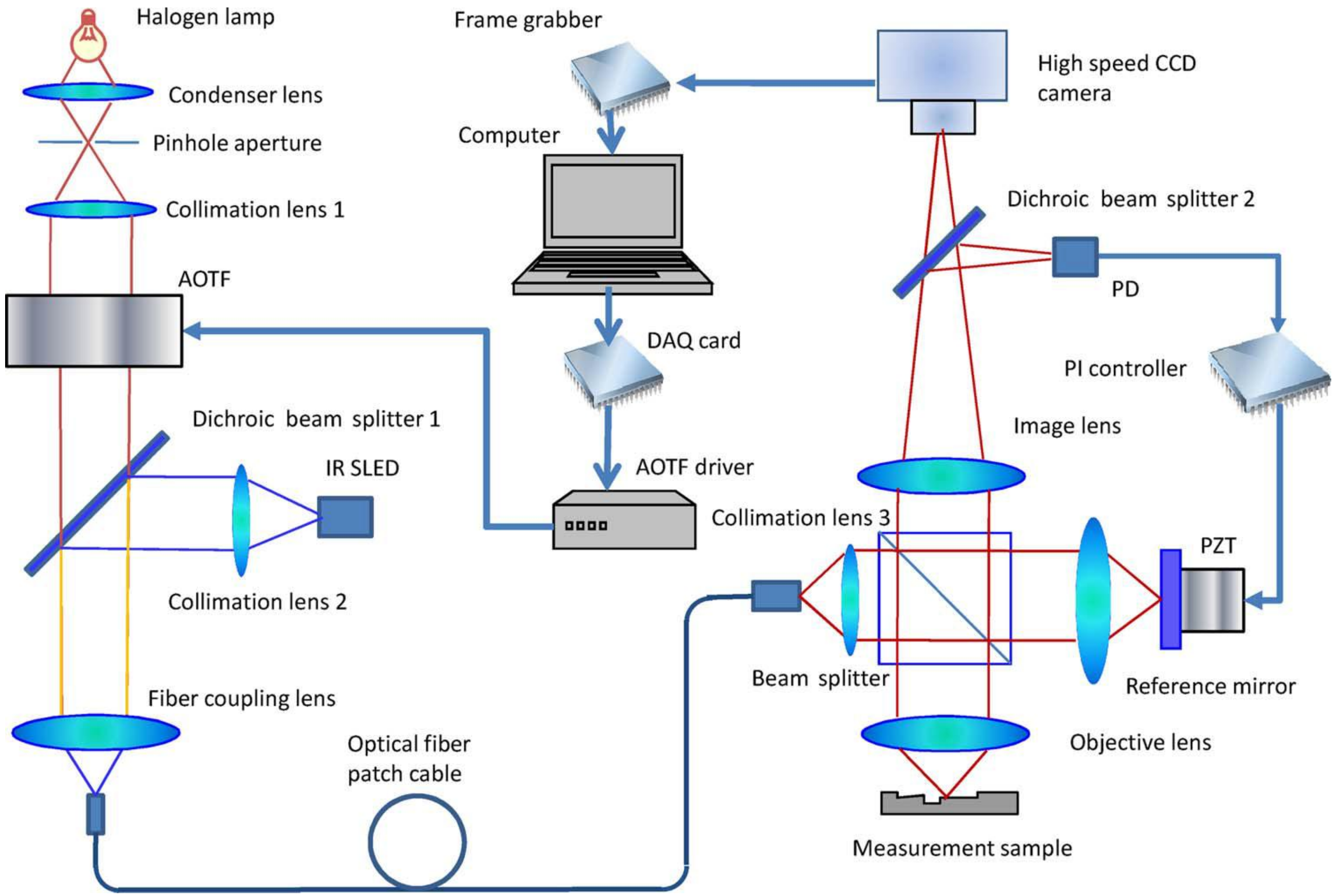
- Detailed defect analysis for each application
  – functional significance assigned to each defect classification
- Wavelength scanning interferometer (WSI) capable of nanometre resolution for inline defect inspection and metrology
- Pragmatic yet ISO-compliant calibration and verification procedures developed
- New metrology tools for beyond the immediate studies:
  – WSI for a moving web
  – resolution enhancement
- Various other achievements in functional barrier application and traceable testing.

SEVENTH FRAMEWORK PROGRAMME

* additional progress to be shared shortly

NANOMEND
METROLOGY FOR ENHANCED NANO-SCALE DETECTION, CLEANING AND REPAIR

Wavelength scanning interferometer (WSI)



Schematic diagram of the Huddersfield WSI

- Concept/design: Huddersfield University
- Component design: IBS precision engineering
- Traceable calibration/ characterisation: NPL

Not shown – new autofocus capability

Jiang X, Wang K, Gao F, and Muhamedsalih H 2010 *Applied Optics* **49** 2903-2909
Gao F, Muhamedsalih H and Jiang X 2012 *Optics Express* **20** 21450-21456
Muhamedsalih H, Gao F and Jiang X 2012 *Applied Optics* **51** 8854-8862

Point probes for HDR metrology

What is a point probe?

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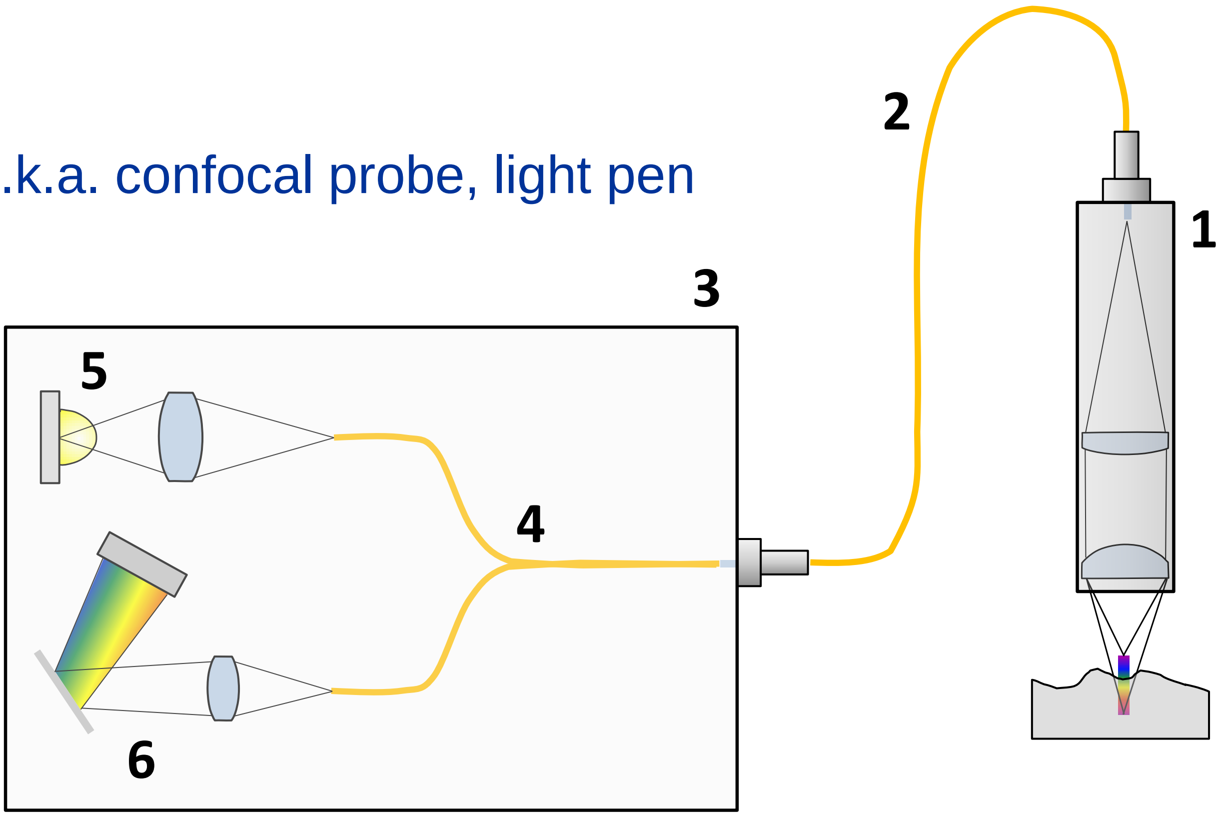
- Detects axial position of surface at a single point

  Fast *z* scan … or ‘optical scale’
- ‘Optical stylus’
- Complete required surface measurement using multiple profiles

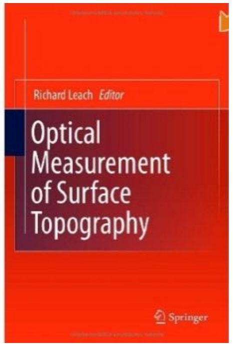
  (far too slow? c.f. stylus instruments)
- Example: chromatic confocal probe

Example: chromatic confocal probe

- a.k.a. confocal probe, light pen



Schema of a chromatic confocal probe system: (1) The probe (final optics); (2) optical fibre connection; (3) the controller unit; (4) optical Y-couple; (5) white light source and (6) the spectrometer, in which displacements, encoded as wavelengths of light, are directed onto an array of pixels (from [5]).



Example: chromatic confocal probe

- Measurement rate – limited by CCD operation
  (DSP, illumination levels, typically ~10 kHz)

- Heavily used as inline non-contact height gauge
  → ✓ robust, ✓ multiple suppliers, ✓ integration,
  ✓ standoff
  (but not perfect)

- Sensor + scanning system: high resolution surface topography

Throughput challenge

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- High resolution *tactile* (point) measurements – very slow

  Very slow: 1 mm^2 takes ~ minutes for 2.5D measurement

- Laser scanning confocal microscope

  Piezo-controlled 3D scan of spot

  Faster: 1 mm^2 takes seconds for 2.5D measurement

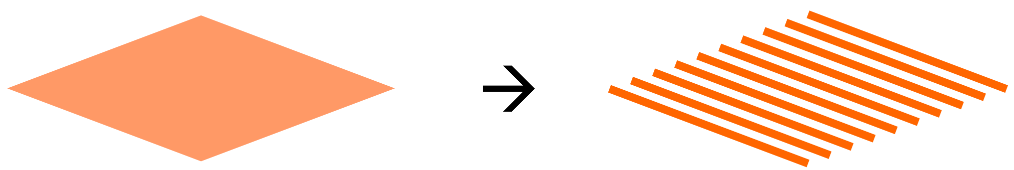
- HDR needs > 10^4 faster – new approach needed

Throughput challenge

- Solution:

  Prior knowledge → simplified measurement

  Reduce dense 2D scan to representative profiles



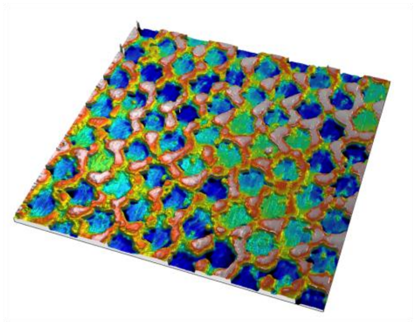
  Not new idea – skill is in the reduction method

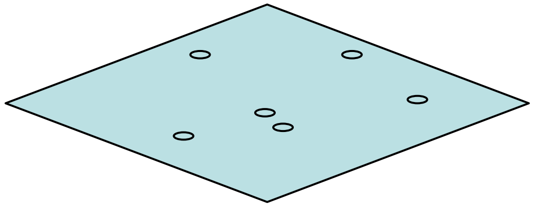
  Best for:

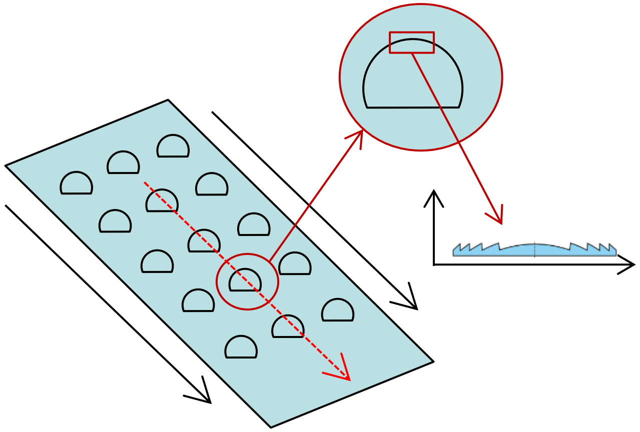
  - Linear features in known location (e.g. CAD)
  - Known symmetry of design

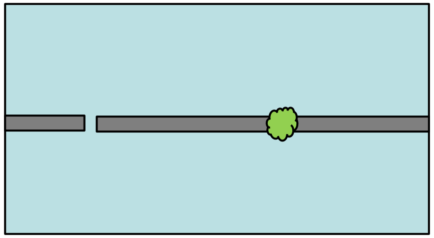
Throughput challenge

- Suitable HDR applications?
  - ✗ 100 % surface topography measurement
  - ✓ Form inspection for micro-optics
  - ✗ Search for dispersed random defects
  - ✓ Continuity defects in linear features









Throughput challenge

- Pessimistic max speed?
  - ✓ Fewer points acceptable?
  - ✓ Faster probes being developed – 70 kHz
  - ✓ Parallel probing – line scanners
- Optimistic max speed?
  - ✗ Real samples are dark
  - ✗ Optical property discontinuities break measurement
  - ✗ Sampling holding / motion problems

Conclusions point sensing

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- Point sensors + brute force measurement → ✗
- Point sensors + careful measurement simplification → ✓

  … in some important applications
- i.e. smarter measurement critical to success in HDR surface metrology and inspection applications
- A priori knowledge critical for use of point sensors in HDR applications
- Independent benchmarking will assist in choosing sensors – under development at NPL

High resolution areal sensors:
where we are?

Review stage

- Focus - common surface topography measurement techniques
  - CCM,
  - point autofocus,
  - confocal microscopy,
  - DHM,
  - WLI,
  - PSI,
  - FVI,
  - ptychography,
- Aim – classification of limitations

Review findings

- Significant shortcomings in measurement throughput.
- Axial scanning to be avoided.
- Significant challenge:

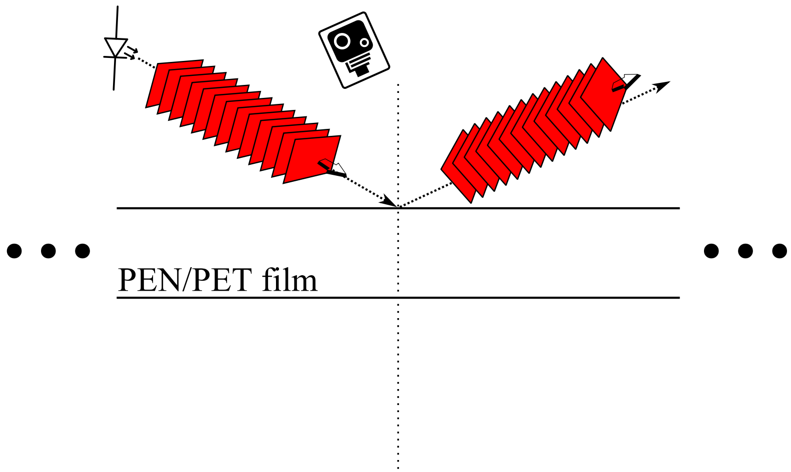
HDR samples typically incorporate all the problematic features one can imagine

DARK-FIELD IMAGING

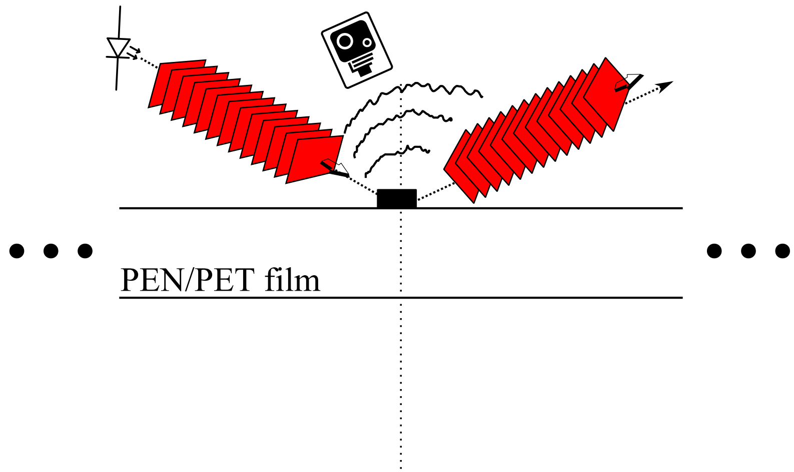
CONCEPT

Dark-field imaging (scattered radiation) should return information on the localisation of areas of interest with reasonable resolution.

No defect:



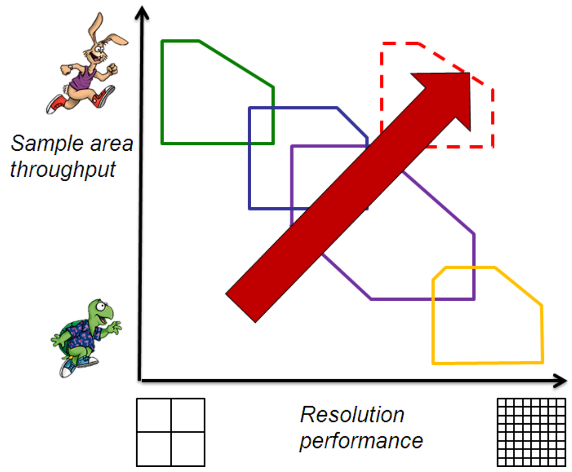
Sample defect:



DARK-FIELD IMAGING

CONCEPT

- TARGET CONFIGURATION: single-line CMOS detector arrangement to cover entire sample
  - lateral resolution with available hardware limited to ~5 to 50 µm



- expected data count for 16k pixel detector ~1 GB/s

DARK-FIELD IMAGING

NEAR FUTURE

- verify concept of single image-frame defect detection;
- verify how far we can push the detection and what is the primary limiting factor;
    - defects smaller then lateral resolution are expected to be visible;
- investigate angular responses of such a configuration;
- investigate responses of such a configuration to multiple wavelength illumination.

BRIGHT-FIELD IMAGING

CONCEPT

In presence of a defect, intensity of recorded radiation should depend on the pair - the depth of the feature and wavelength of illumination. This is due to changes in phase differences for a given depth with regard to the wavelength.

- For this reason, with carefully selected illumination conditions additional information about defect should be accessible.

BRIGHT-FIELD IMAGING (2)
A BIT MORE DISTANT FUTURE

Conduct experiments to check and learn:

- if said differences at normal incidence illumination can be detected.
- how to select optimal wavelengths.
- how illumination source type influences the ‘measurement’.

Resolution enhancement

Super-resolution – The NPL view

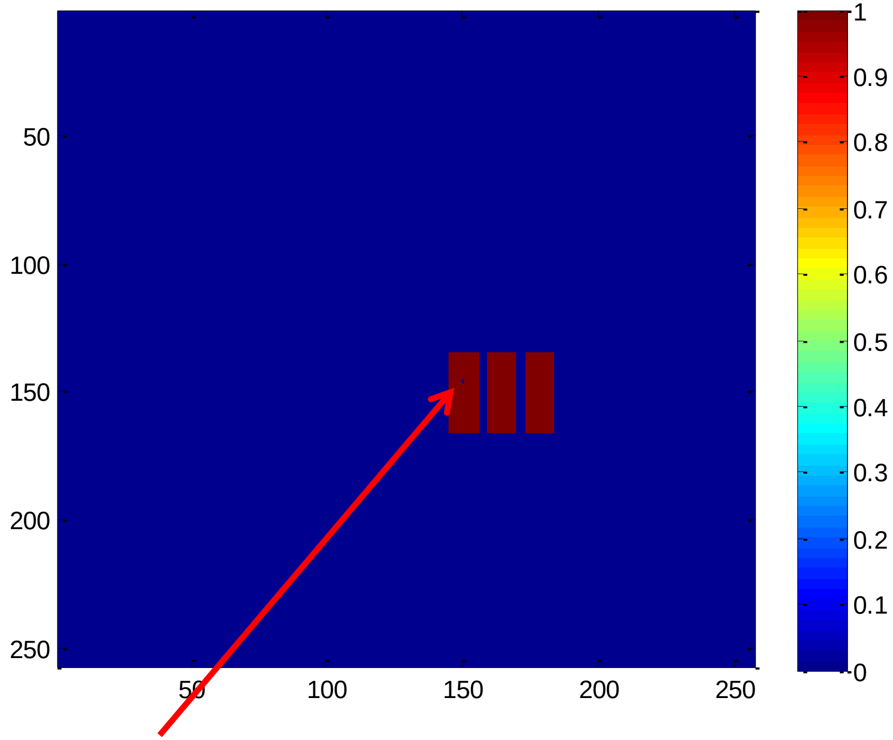
- SR is the recovery of object information that is lost during the imaging process
- Strictly, SR is the recovery of spatial frequencies that exceed the bandwidth of the imaging system transfer function.
- SR techniques broadly fall into three categories:
    - Computational
    - PSF engineering
    - Fluorescence based (Stimulated emission depletion, nonlinear saturated structured illumination, photo-activated localisation, stochastic optical reconstruction)
- At NPL we aim to maximally exploit *a priori* knowledge of the object to enhance the image resolution
- Computational SR techniques show promise for on-line defect detection

SR and defect detection

- Manufactured surfaces often accompanied by information that describes what they should look like
- This *a priori* knowledge is a powerful ally in quest for SR
- Example: 2D model fitting approach
- *A priori* knowledge: we are looking at 3 rectangles (size, shape, position and orientation unknown)

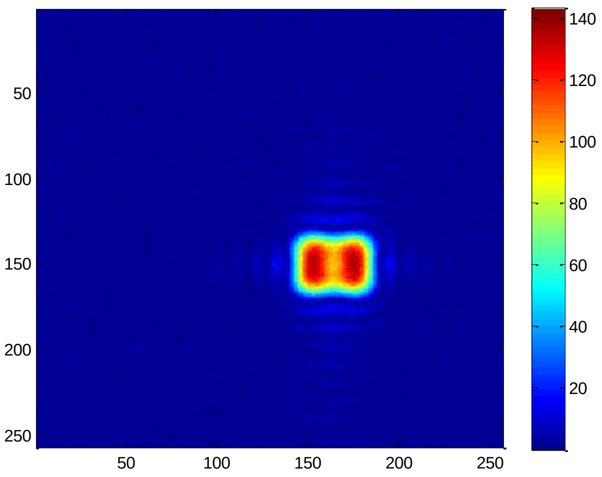
SR and defect detection

Object (three identical rectangles with a different reflectance to the uniform background)



Defect

Image (with 10% white noise)



Object not resolved and no evidence of defect

SR and defect detection

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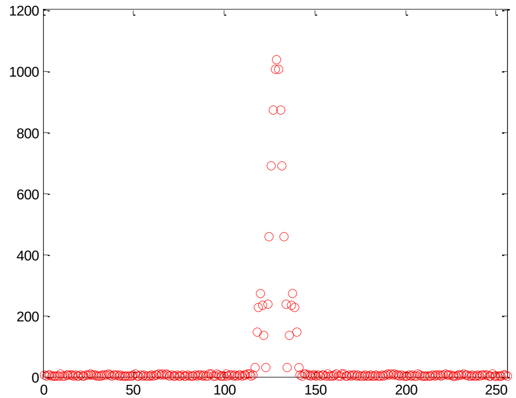
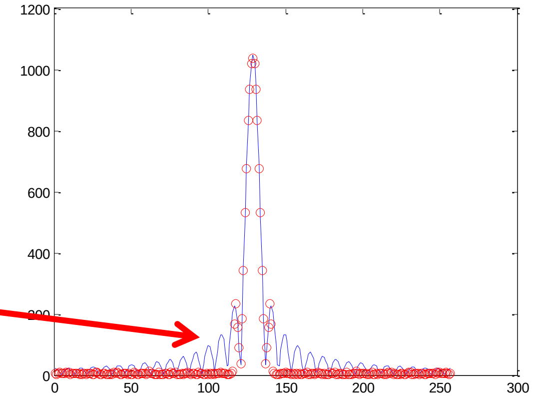
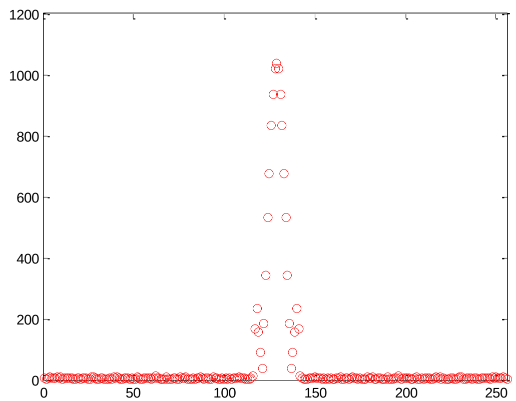
Take Fourier transform of image

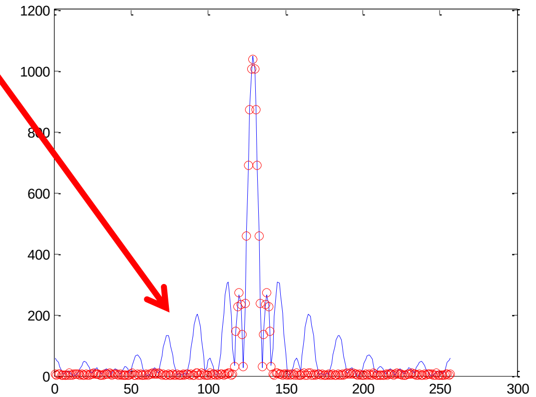
Use *a priori* knowledge to fit to Fourier data and extrapolate beyond bandwidth





Recovered object data





SR and defect detection

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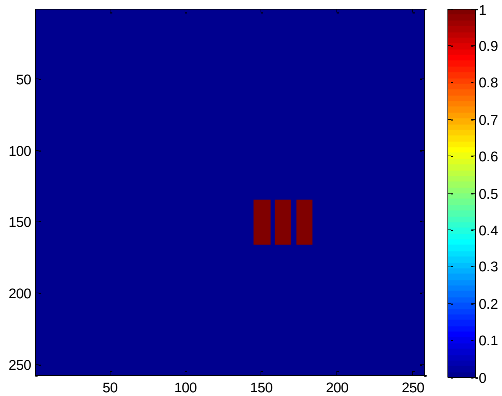
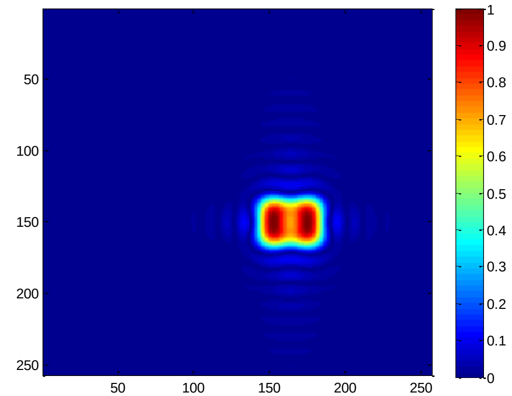
Inverse F.T. recovered data

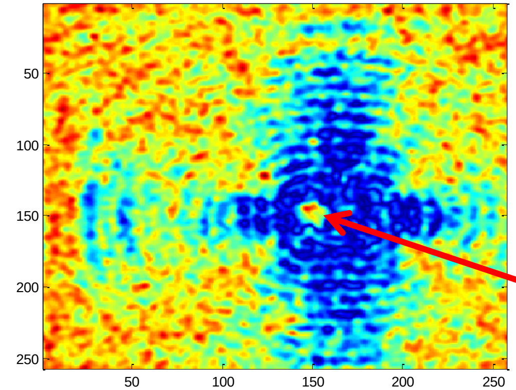


Convolve recovered object data with PSF



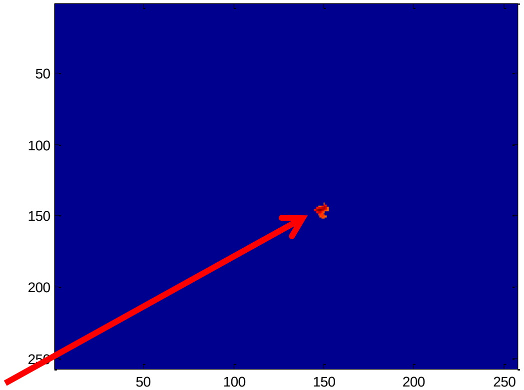
Note: Information regarding defect has not been recovered

Subtract original image from new image



Defect

Subtract a reference image



Defect

SR and defect detection

- Early stages for this work at NPL
- Numerical simulations show technique has some promise
- Prototype coherent imaging system under construction to test methods on real image data
- Methods to make data fitting faster & more robust to noise being researched

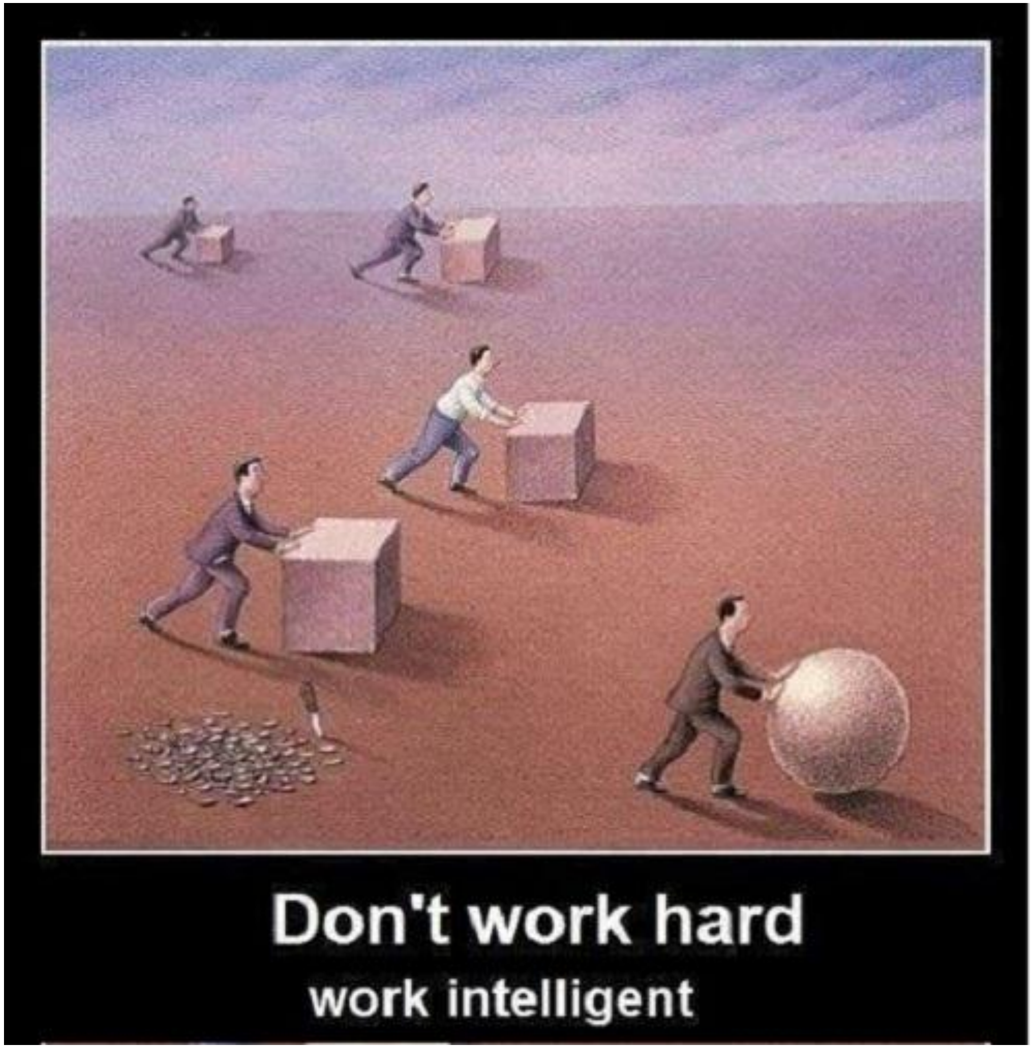
Other things to look out for

- Intelligent sampling
- Hybrid instrumentation and data fusion
- Compressed sensing
- Amount of data?
- …

Conclusions

- There has been a great deal of work to develop large area, low resolution form measuring instruments
- and small area, high resolution texture measuring instruments
- We now need to combine the two – there is a lot of work to do on basics *plus* working *in* industry
- NPL is actively searching for industry partners to work with in this area – we can potentially match funding using NMS projects

Measure smarter, not harder!



Thanks to…

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