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Advances in metre traceability for Industrial Process Control

Dr Chris Jones (christopher.jones@npl.co.uk)
Dimensional metrology

MetMap 2019: Integrated Metrology for Precision Manufacturing
22 - 23 January 2019, Knowledge Transfer Centre
Advanced Manufacturing Research Centre, Sheffield, UK

Reminder – measurement traceability

- “property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations**, each contributing to the **measurement uncertainty**” [VIM: https://jcgm.bipm.org/vim/en/2.41.html]

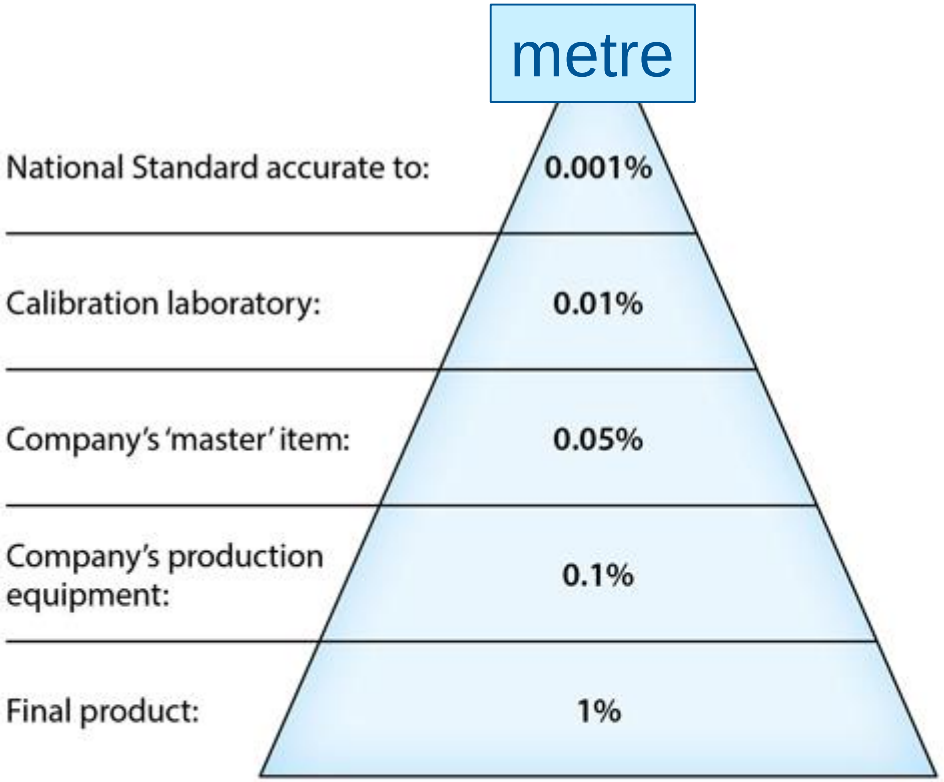
From a calibration perspective:

- measuring equipment should be tested against a standard of higher accuracy (and so on up the chain).

From a industrial user’s perspective:

- The further you are from the relevant SI unit, the larger your uncertainties are likely to be

Traceability is a useful qualifier for post-production quality control reporting for products, but what about for process control?



How is traceability relevant to process control?

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the process engineer

Traceability can be a source of information and process improvements.

A good handle on traceability (and the associated good metrology practice) allows you to:

1. objectively quantify performance of instrumentation and measurement procedures

2. prioritise your metrology investments based on expected return

(and once you're happy your metrology is fit for purpose:)

3. objectively compare inspection data over time and between instruments

… to achieve small but consistent improvements that keep a volume process competitive.

The cost of measurement uncertainty
…or the value of managing it

Image courtesy of Airbus – partnered in LUMINAR to solve this problem

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Airbus A350 XWB wing

Compensation for refractive index and turbulence effects in large factories

1000 kg extra metal in a large aeroplane!

(not just Airbus – industry-wide problem!)

LUMINAR

NPL OPTIMUM – 3D coordinate measurement system

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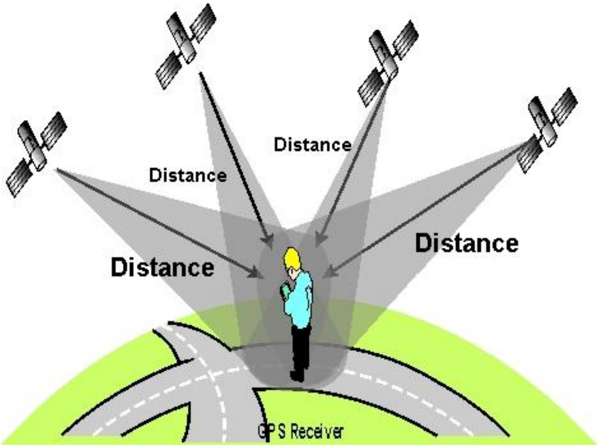
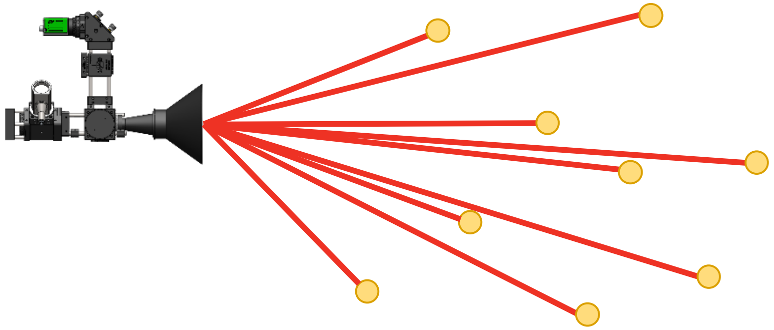
Multilateration

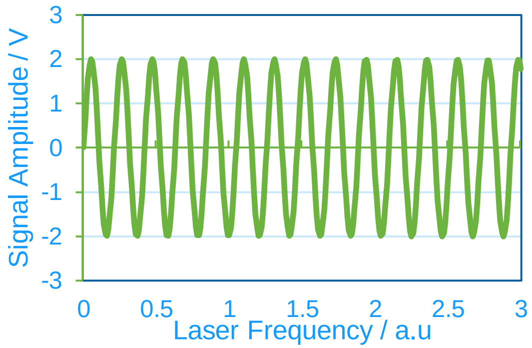
“Indoor GPS”



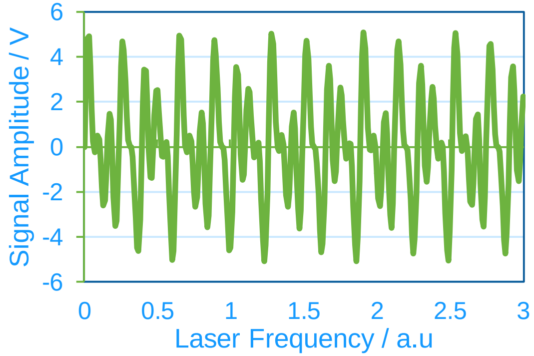
Frequency Scanning Interferometry



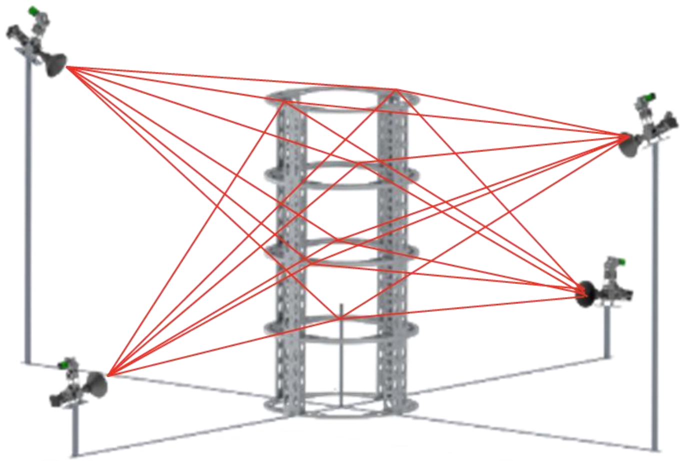
Single target



Multi-target



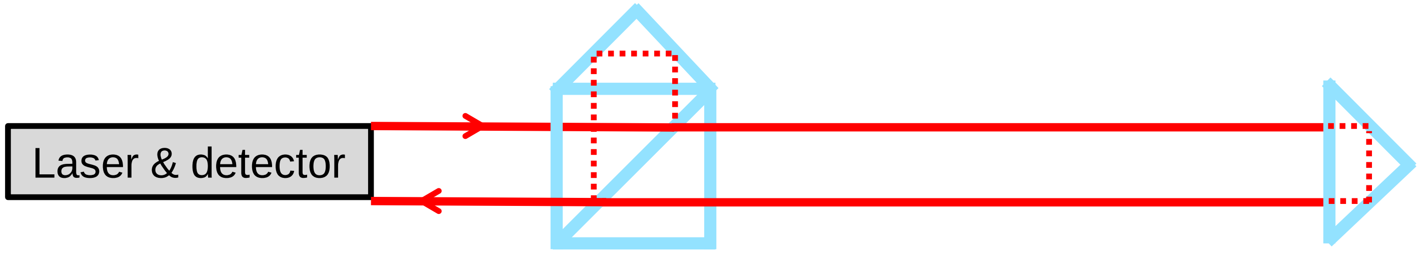
OPTIMUM

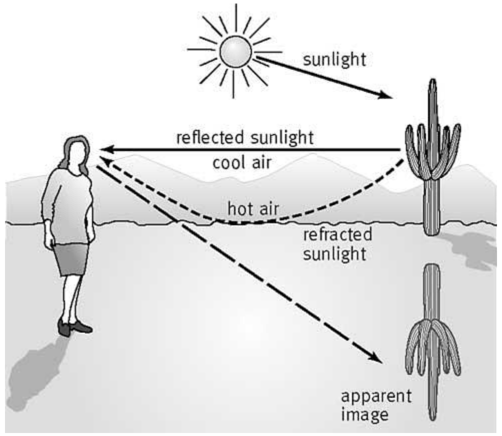


- Accurate (5:10^6)
- Real-time uncertainties, target-specific
- Traceable
- Self-calibrating (HCN gas cell (λ), *c.f.* on-board atomic clocks for real GPS)
- Flexible

Prioritising metrology investment – an example

environmental monitoring for refractive index compensation





Displacement interferometer: 1 fringe = λ/2 ≈ 0.3 µm

But $\lambda = \lambda_{vac}/n$ where the refractive index n = 1.000 2XX XXX

Uncompensated → wrong distances! (parts in 10^5)

Refractivity $(n-1)_{tph} = K_{\lambda} D_{tph}$ (Edlen and others)

- a dispersion term (λ)
- an air density term → measure temperature, pressure, humidity

Prioritising metrology investment – an example

environmental monitoring for refractive index compensation

Suggested additional column, for process control analysis

Uncertainties from high-accuracy sensors used in dimensional applications

Parameter	Sensor	Typical cost (including calibration)	Best standard uncertainty in application	Influence on refractive index (meast. uncertainty, in general terms)	Added value for process control loop
Equations	-	-	$1 \cdot 10^{-8}$	$1.0 \cdot 10^{-8}$	…
Pressure	Vibrating Si barometer	£3,000	0.05 hPa	**1.4** $\cdot 10^{-8}$	…
Temperature	Platinum resistance thermometer, AC bridge	£7,000	0.05 °C	**-4.6** $\cdot 10^{-8}$	…
Humidity	Chilled mirror dewpoint meter	£3,000	0.7 %RH	$0.7 \cdot 10^{-8}$	…
CO_2	IR absorption in cell	£1,000	50 ppm	$0.7 \cdot 10^{-8}$	…
TOTAL	**[summed in quadrature]**	**£14,000**		$\mathbf{5 \cdot 10^{-8}}$	**…**

This column generalises to *contribution to measurement uncertainty*

Objective comparison of data

Traceability is essential to objectively compare/exploit measurement data:

- between instruments – lab to line, or between candidates
  - how do you validate inspection data from a fast, reduced resolution inline sensor against your lab-build defect model, without calibrating sensor metrological characteristics?
- over the history of a process
  - how do you know if your process is changing over time if you don't have a stable reference?
- across a supply chain
  - E.g. defect maps on R2R products

- Obvious link between measurement traceability and data traceability/provenance
  - Digital calibration certificates, data storage formats (X3P, etc), metadata

Case study: traceability for process control

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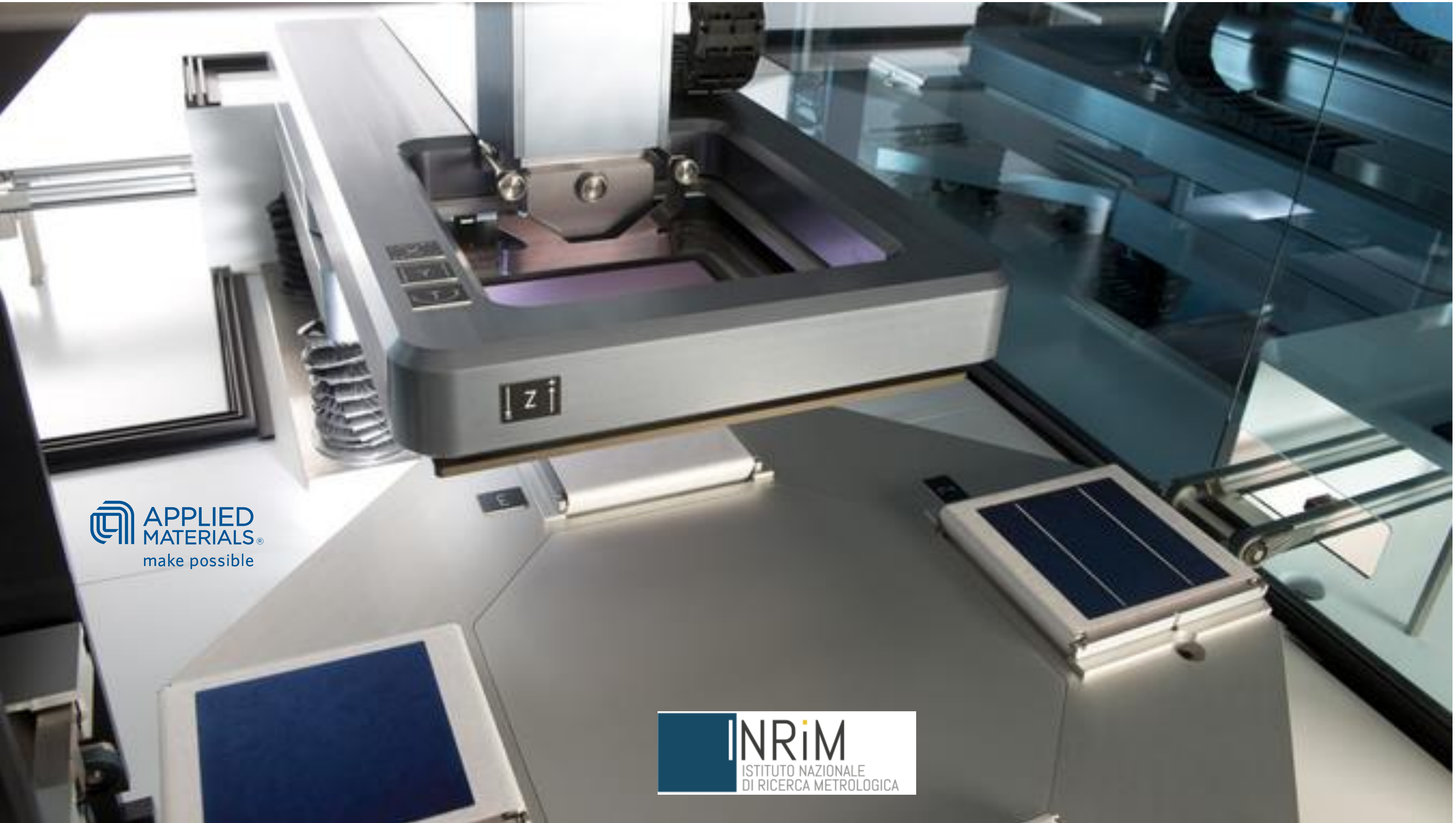
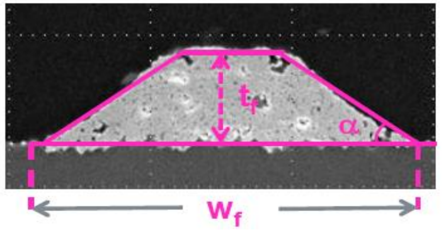
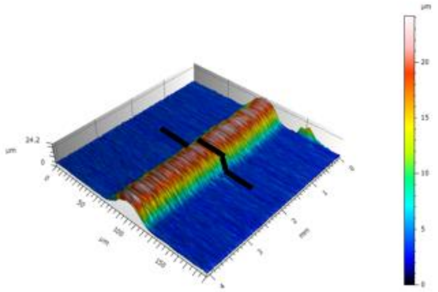


Screen printed fingers on conventional solar wafers





Met HPM

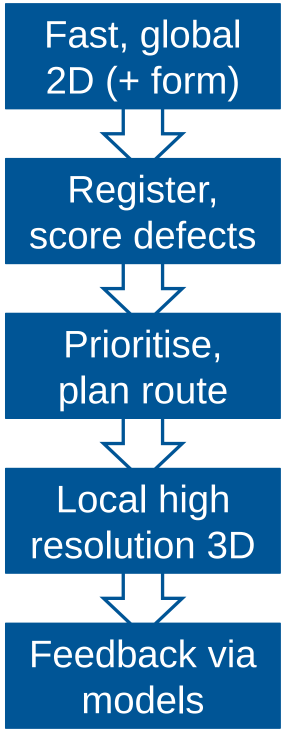
How to achieve much faster 3D inspection?

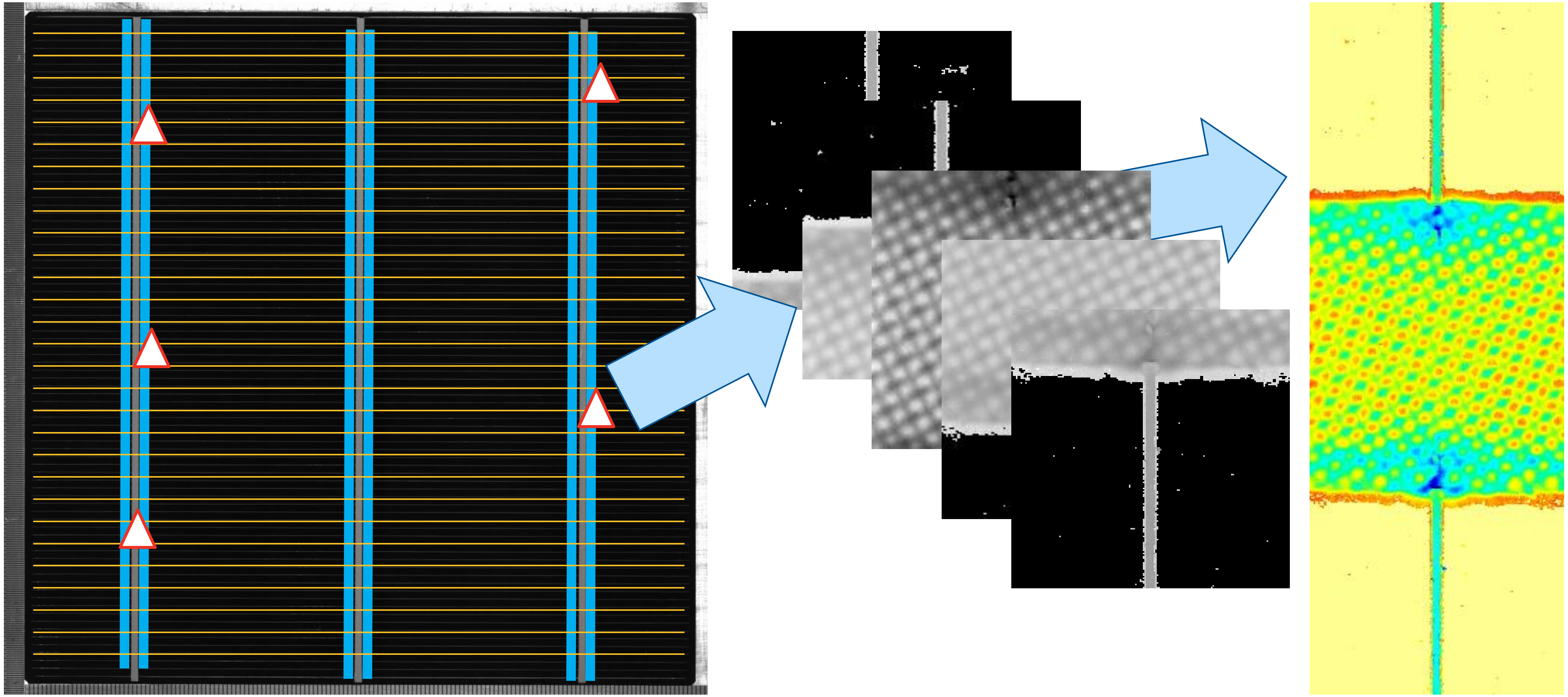
- Choose faster, better spec sensors
- Measure each item more efficiently
- Reduce the proportion of items inspected

…while minimising loss of meaningful inspection capability

Screen-printed electrodes on a-Si PV wafers

Our solution for measurement throughput





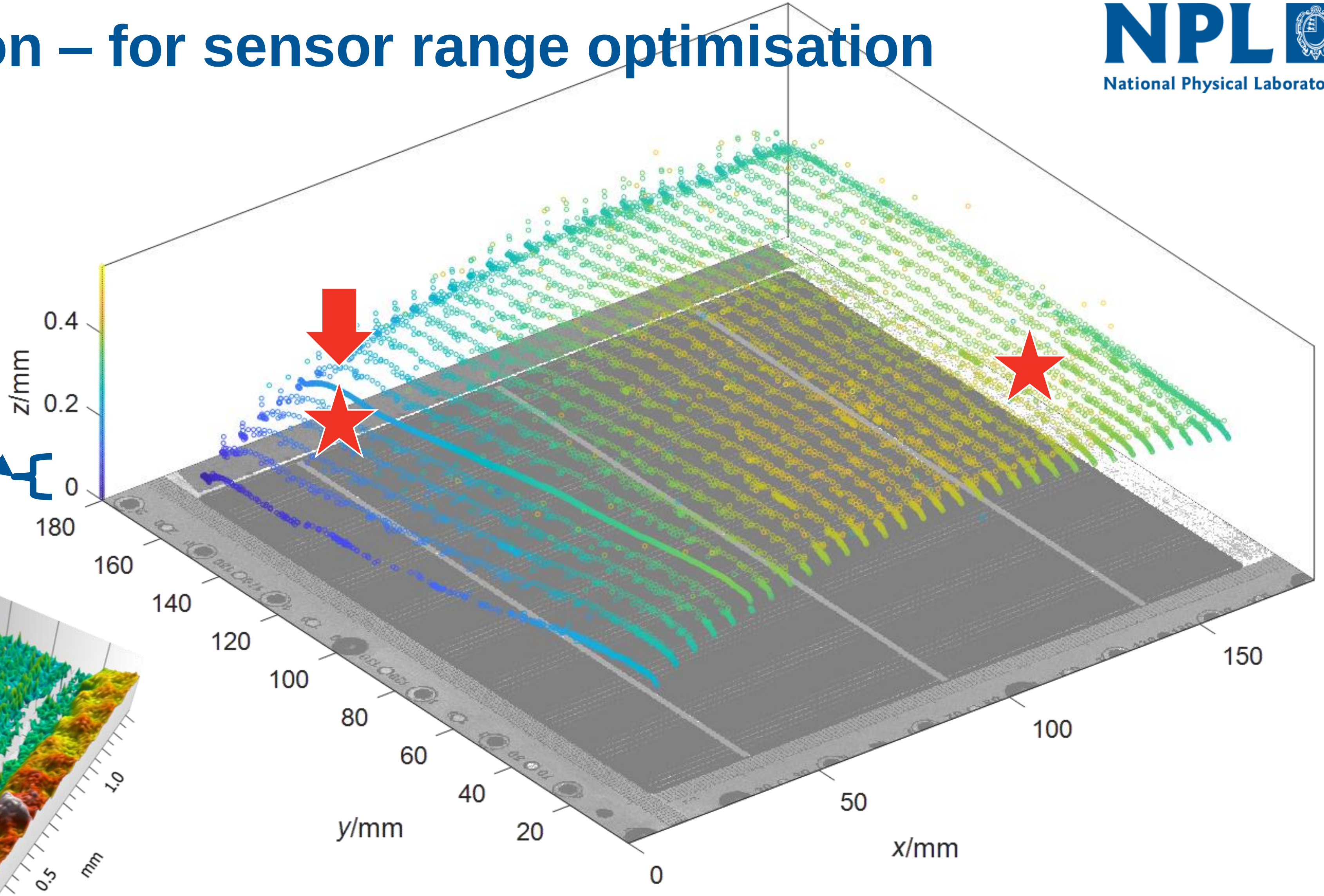
High resolution vision data

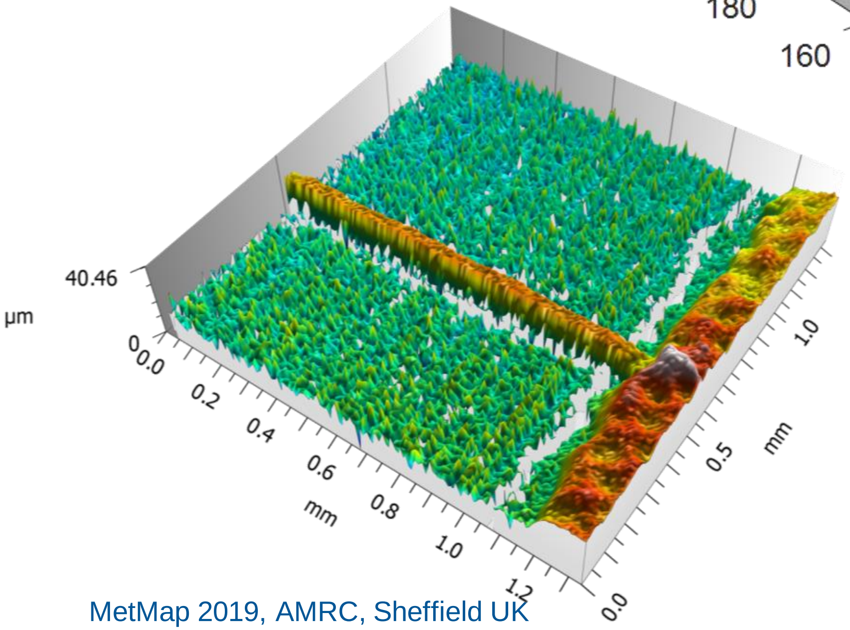
Local 3D topography

Jones CW and O'Connor D 2018
Meas. Sci. Technol. **9** 074004

Form anticipation – for sensor range optimisation

Problem:
High resolution
3D sensor range
only 0.1 mm !



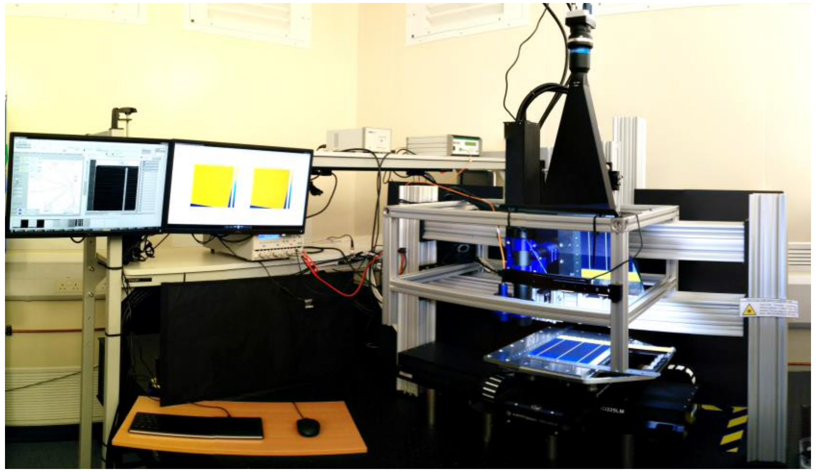


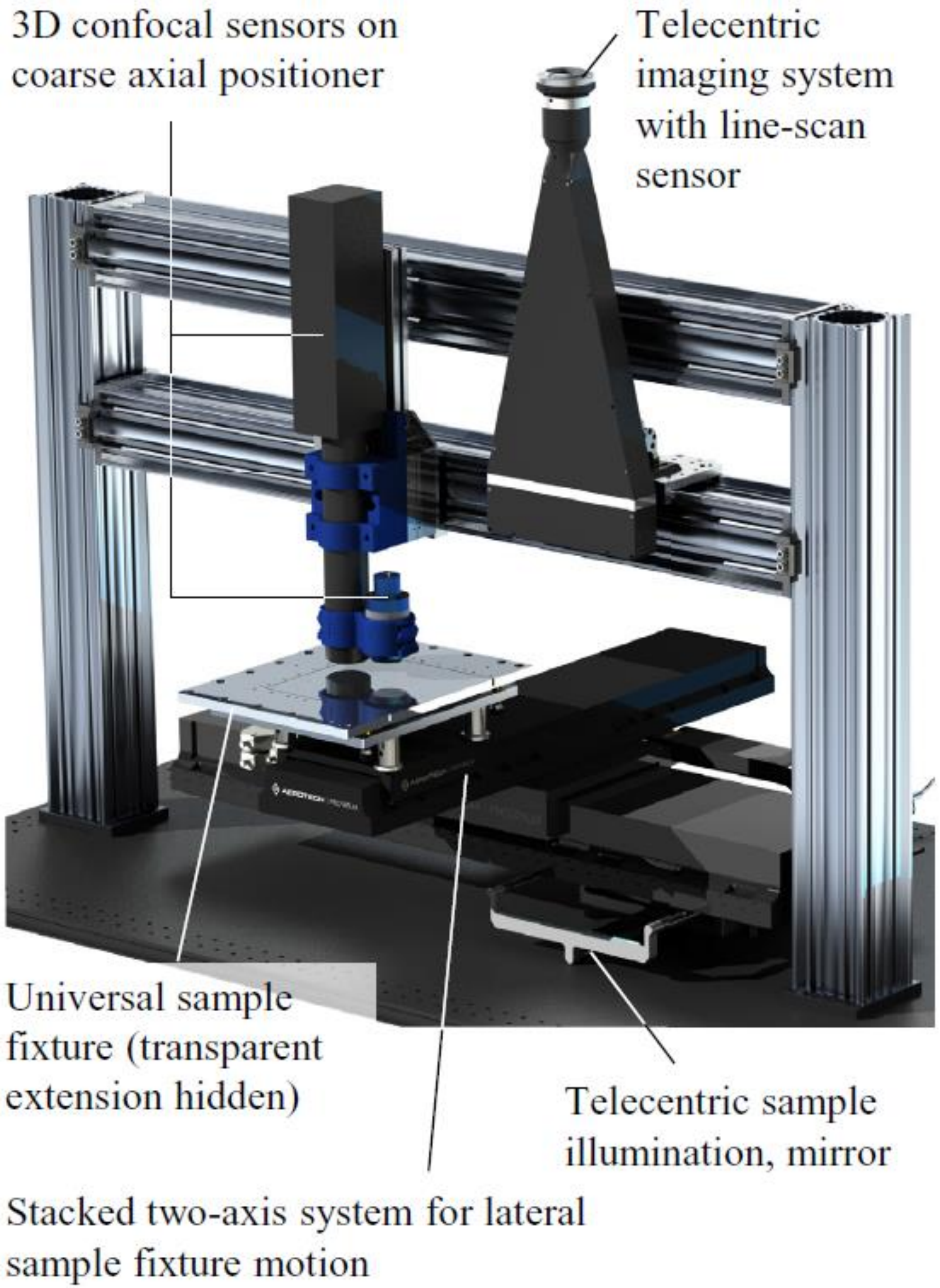
MetMap 2019, AMRC, Sheffield UK

Jones CW and O'Connor D 2018
Meas. Sci. Technol. **9** 074004

NPL hybrid 2D/3D metrology platform

- 640 Megapixels per second **2D**
  (8000 pixels covering 180 mm width)
- 360 kilopixels per second **3D**
  (180 pixels covering 1 mm width)
- Room for other sensors e.g. functional mapping

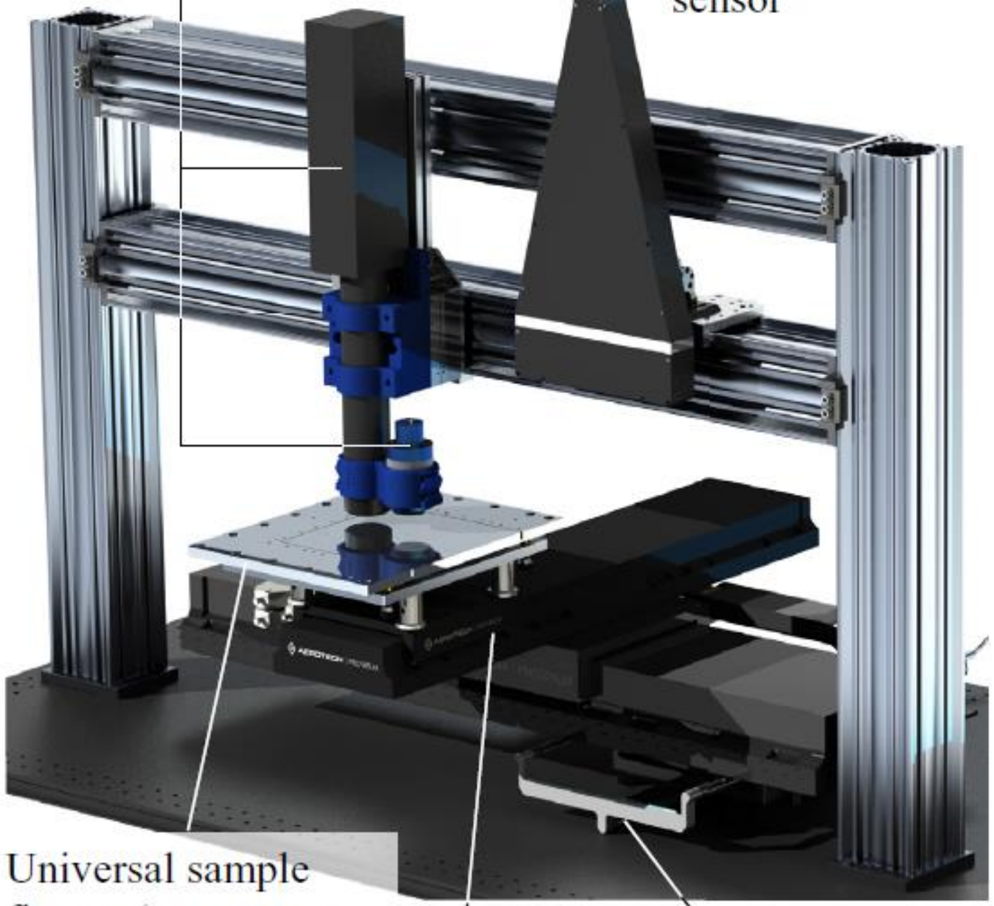




Jones CW and O'Connor D 2018 *Meas. Sci. Technol.* **9** 074004

NPL hybrid 2D/3D metrology platform
Traceability

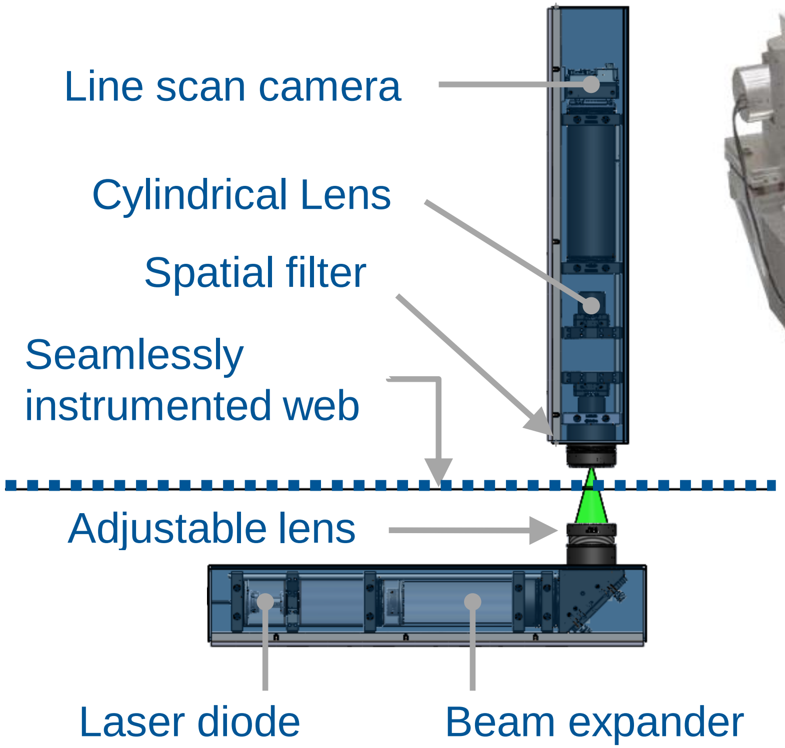
- XY stage encoder scales
  Calibrated Zygo HeNe laser (ad hoc comparison)
- Vision system
  bespoke adjustment and calibration artefact
- 3D topography sensors (form and feature)
  Areal standard

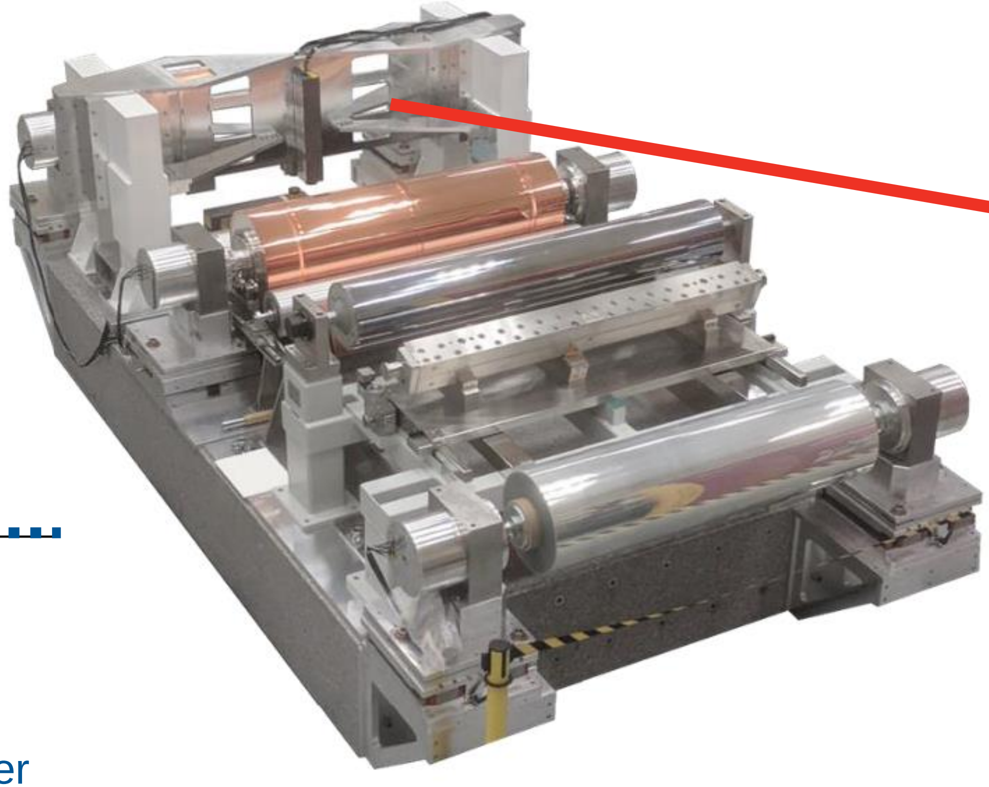


Jones CW and O'Connor D 2018 *Meas. Sci. Technol.* **9** 074004

Hosted development on hybrid metrology platform

Optical encoder system for precision steering of grating-instrument substrates





Sub-micrometre position measurement ability!

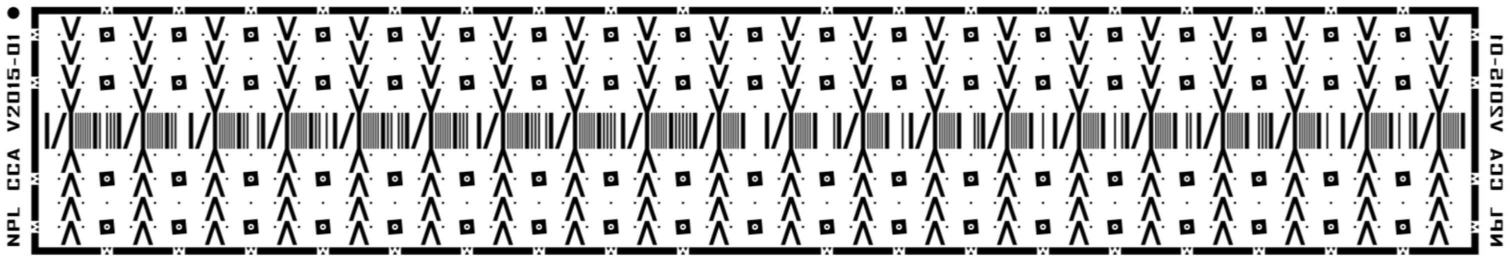
NPL hybrid 2D/3D metrology platform
Traceability

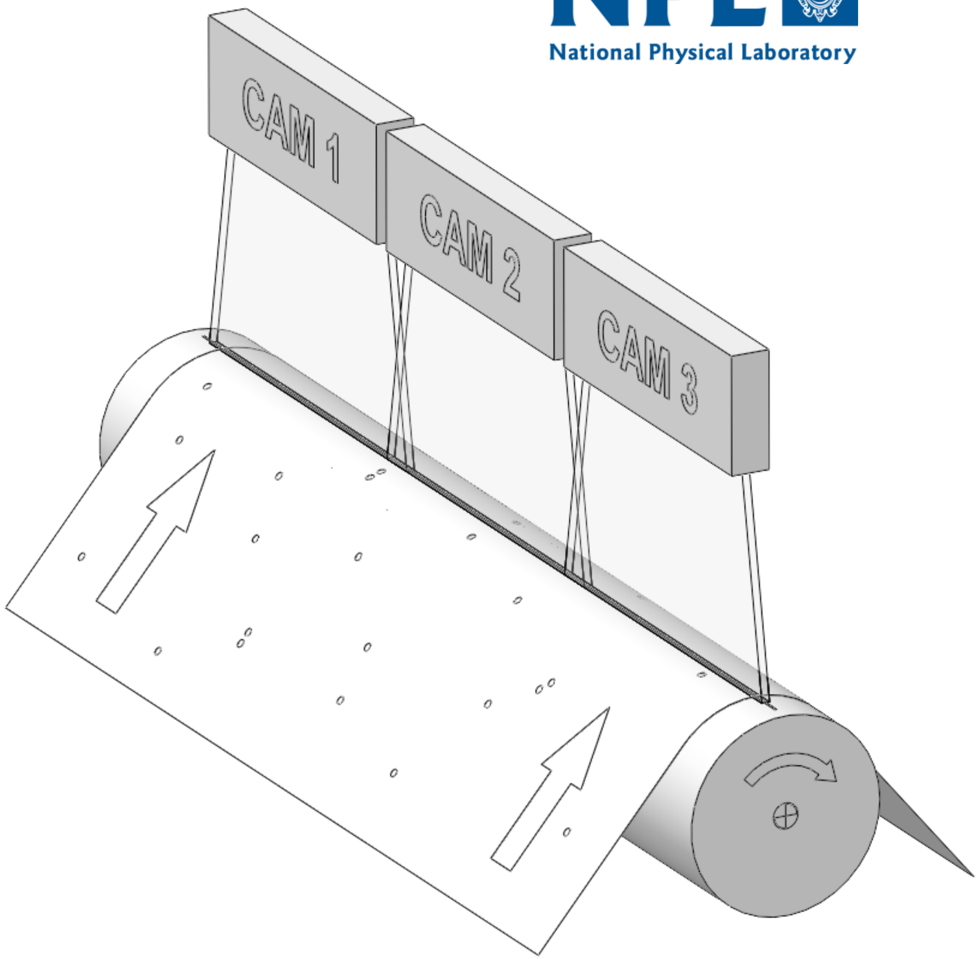
- XY stage encoder scales

  Calibrated Zygo HeNe laser (ad hoc comparison)

- Vision system

  bespoke adjustment and calibration artefact





- 3D topography sensors (form and feature)

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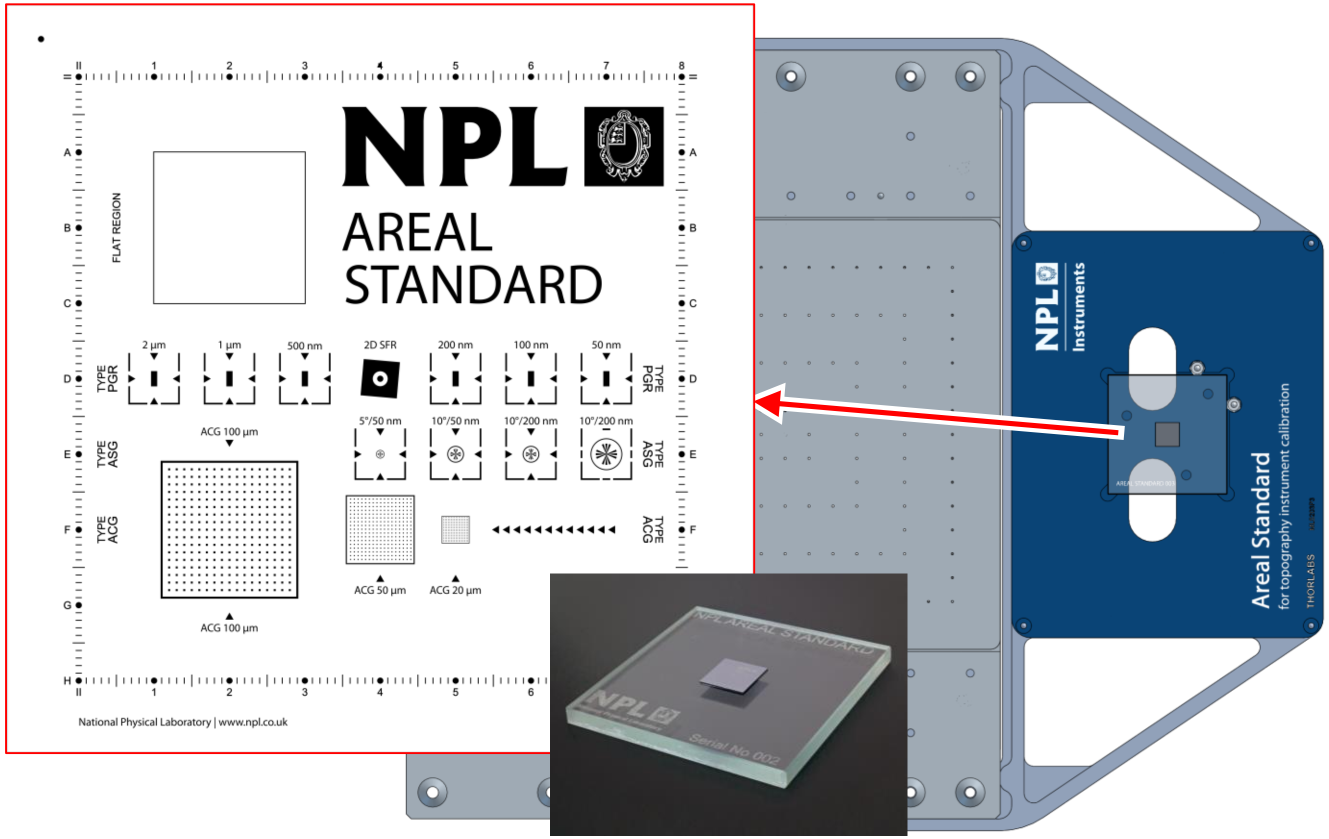
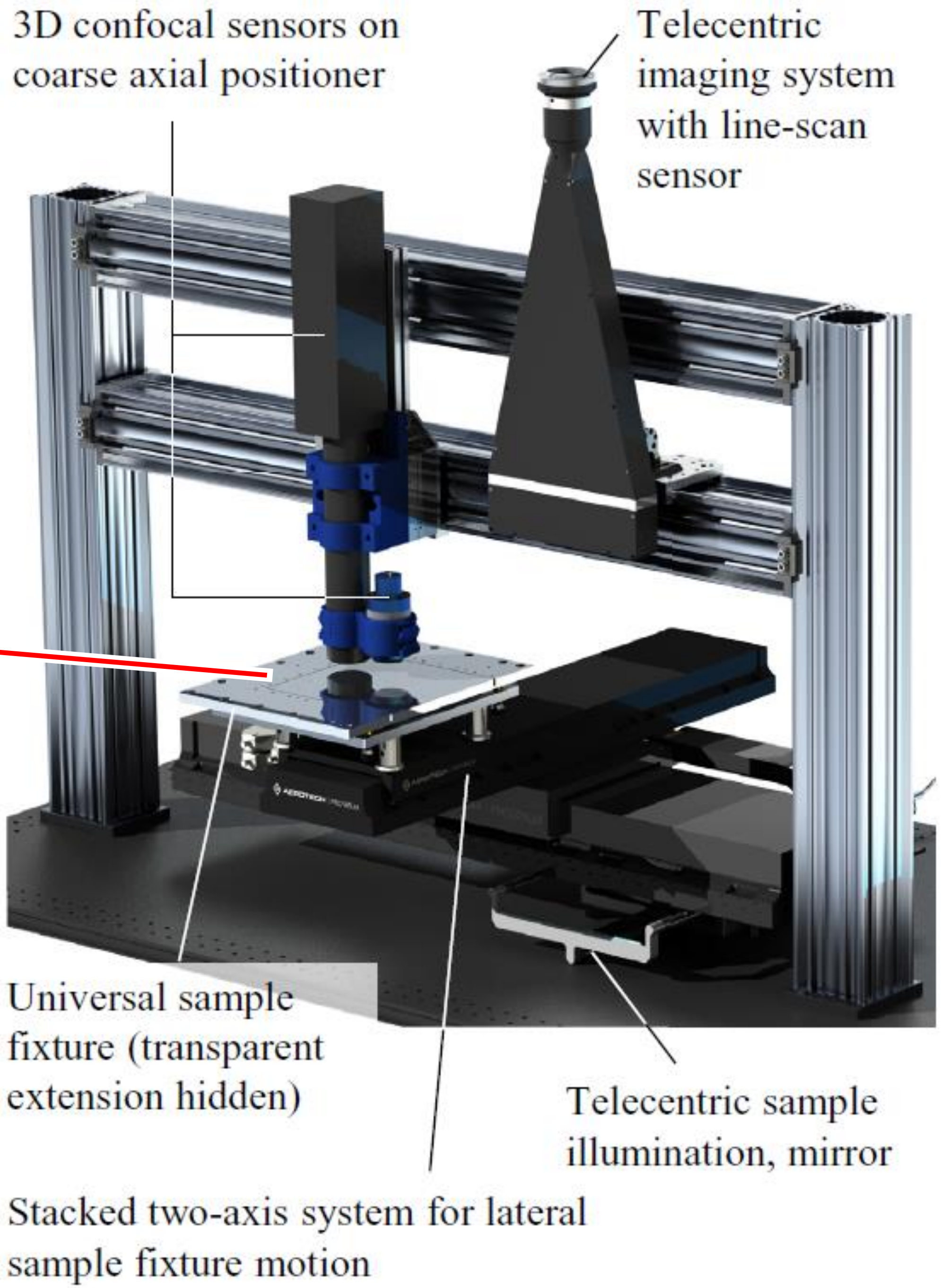
NPL hybrid 2D/3D metrology platform

Traceability





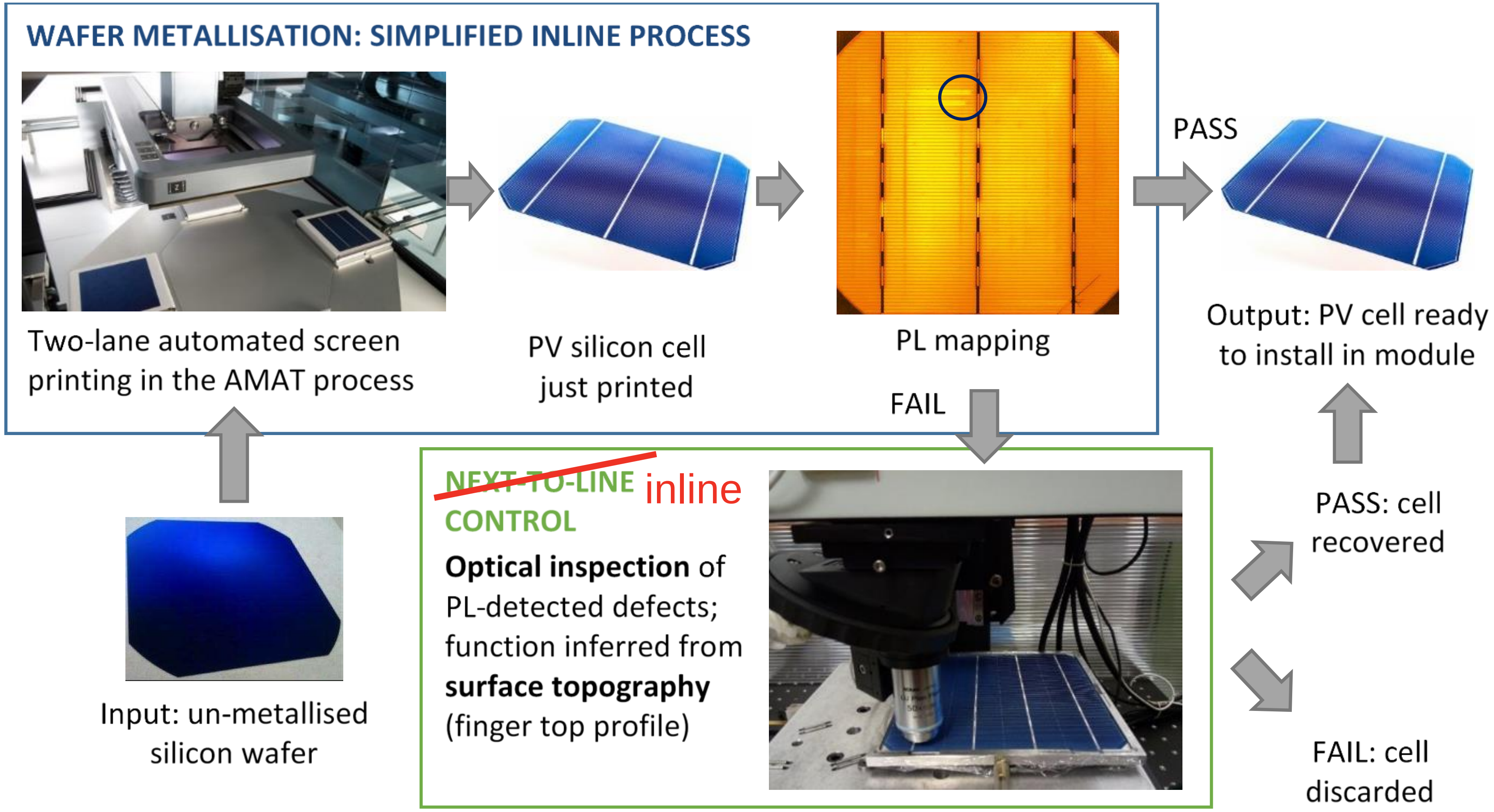
- 3D topography sensors (form and feature)

  Areal standard

To be presented at Lamdamap 2019
Nimishakavi, Jones, Giusca

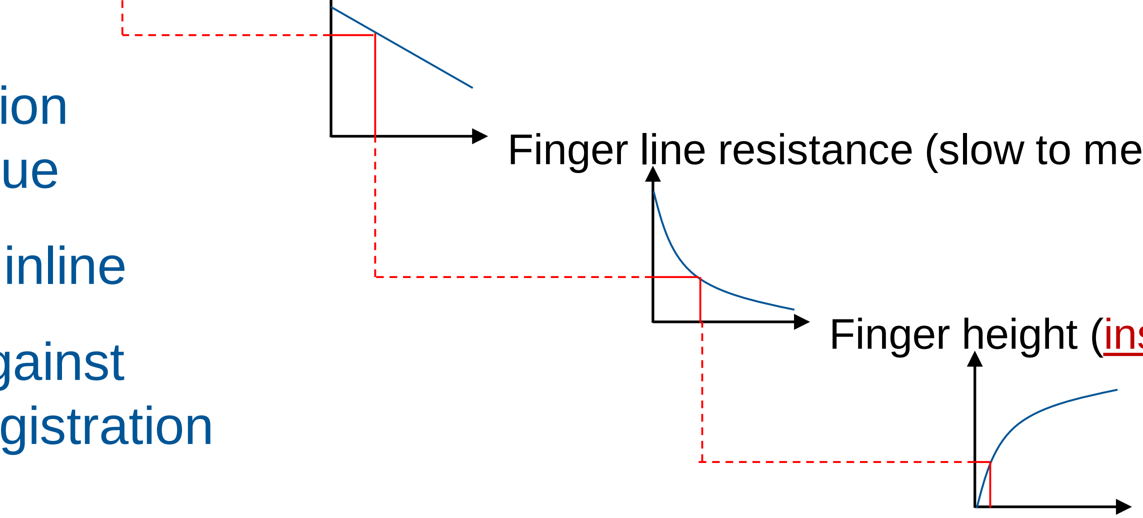
Faster 3D: Reduce the proportion of items inspected

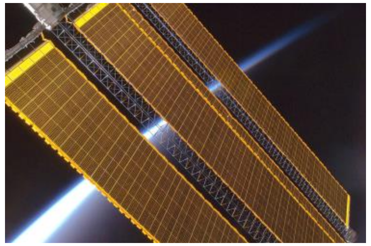
- Understand the rate of process deterioration → reduce the frequency of measurement
  - Exploit data history – traceable data archive – e.g. via supply chain
  - Temporarily divert proportion for slower, more comprehensive inspection



Traceability for process control models

The production engineer's challenge

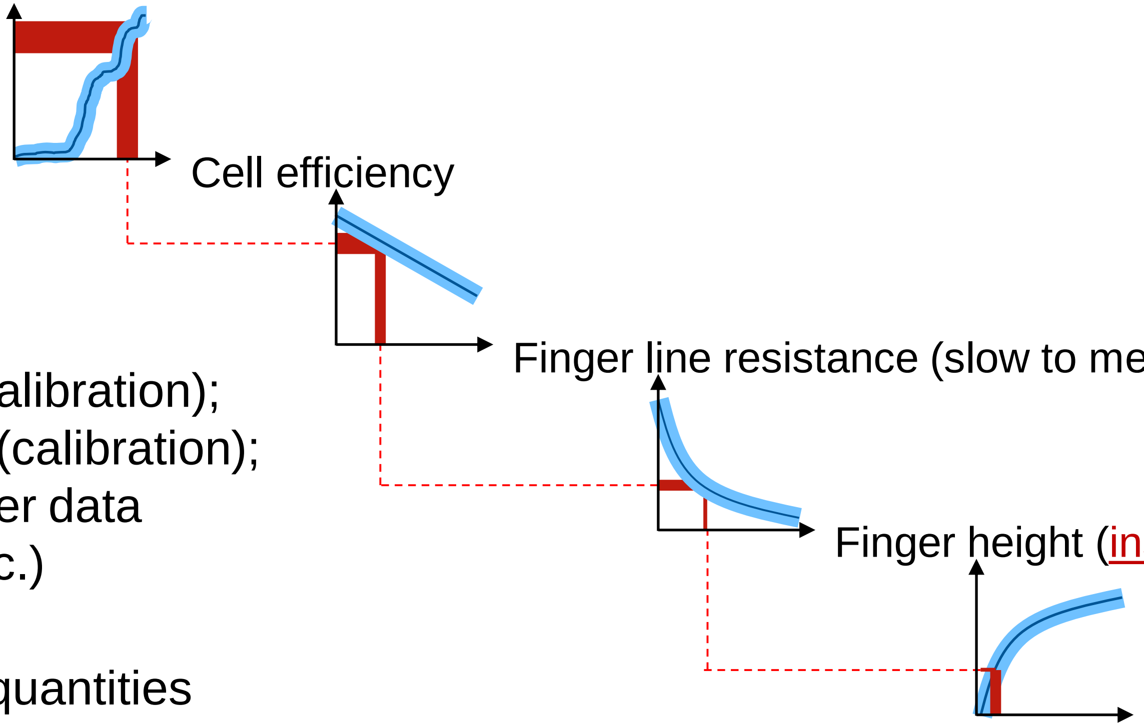




- Link a convenient inspection measurand to product value
- Offline models enhanced inline
- Quantify the link; verify against models (needs reliable registration of data sets)
    - Need efficient, <u>traceable</u> labs!
- Correlate process parameter(s) to inspection measurand (or function)

Traceability for process control models

The production engineer's challenge



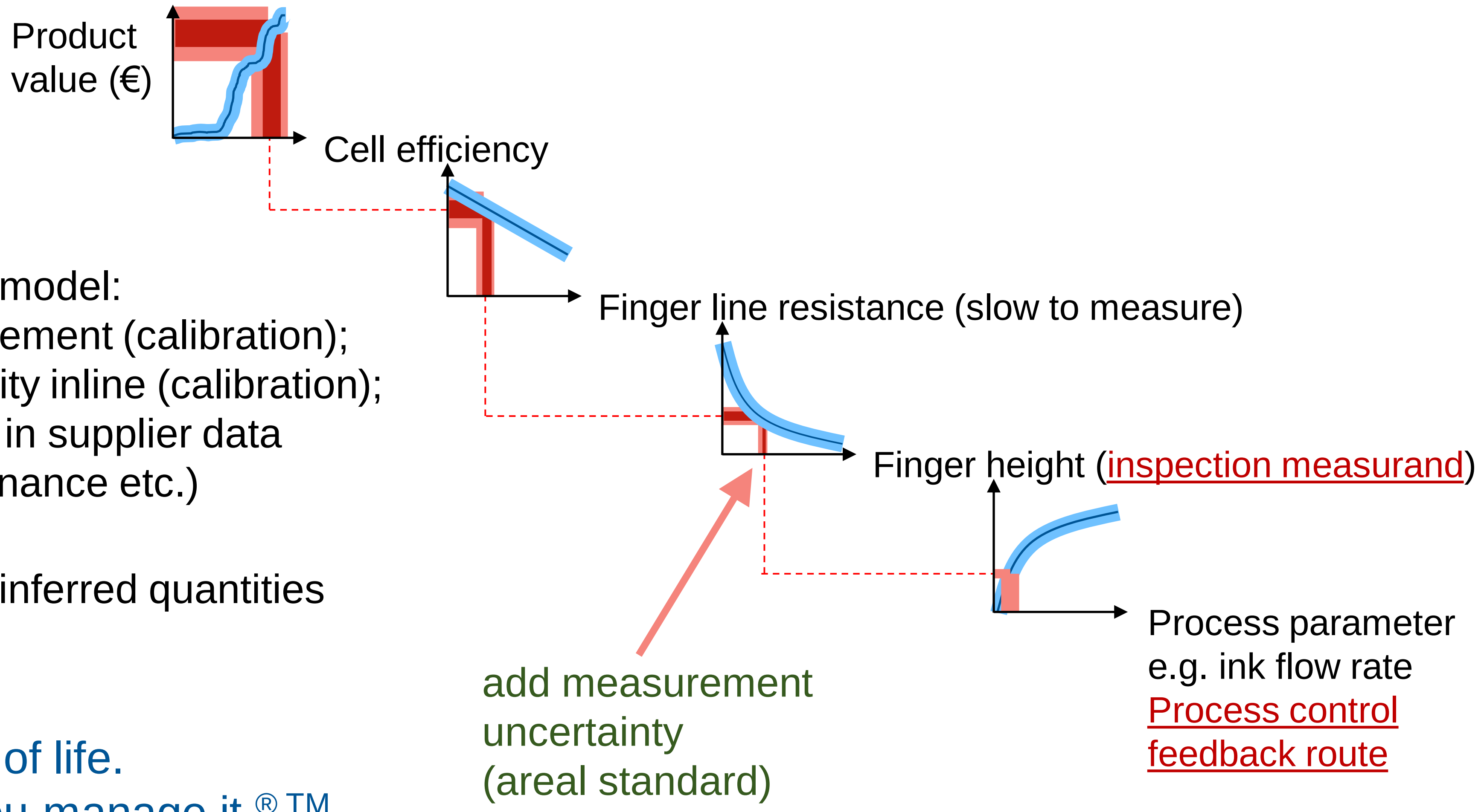
= uncertainty in model:
→ lab measurement (calibration);
→ transferability inline (calibration);
→ confidence in supplier data (data provenance etc.)

= uncertainty in inferred quantities

Uncertainty is a fact of life.
Traceability helps you manage it.® TM

Traceability for process control models

The production engineer's challenge



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Uncertainty is a fact of life.
Traceability helps you manage it.® ™

Summary: traceability allows you to:

- Evaluate/qualify the links/correlation (homework)
  - Efficient, traceable lab operations, with big data support (enable comparison to in-process data)
- Recognise the finite performance of your metrology kit
  - Artefacts – calibration of MCs
- Direct your investment in better sensors
  - Traceability for confidence in specifications and objectivity in acceptance testing
- Improve your process and your competitiveness!

14IND09 Metrology for highly parallel manufacturing

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Thanks for listening!

Contact me for more info:
cwj@npl.co.uk

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BONUS SLIDES!

For interest: EUCOM
(new European metrology project)

EUCoM
Evaluating Uncertainty in Coordinate Measurement

Overview:

- Methods currently in use for determining task specific measurement uncertainties on CMM either involve making time consuming comparison measurements (ISO 15530-3) or using one of the many software applications that enable Monte Carlo simulations to be performed as described in ISO 15530-4.
- Identified within Europe that there is a need to develop **simplified and validated methods for predicting the uncertainty of task-specific coordinate measurements in industry** as well as a need to developing traceable methods that improve the validity of existing methods.

Partners include INRIM (coordinator), IK4 Tekniker, Metrosert, NMIJ-AIST, NPL, CMI, DTI, PTB, TUBITAK, ATH, UNIPD, GUM.

For interest: EUCOM
(new European metrology project)

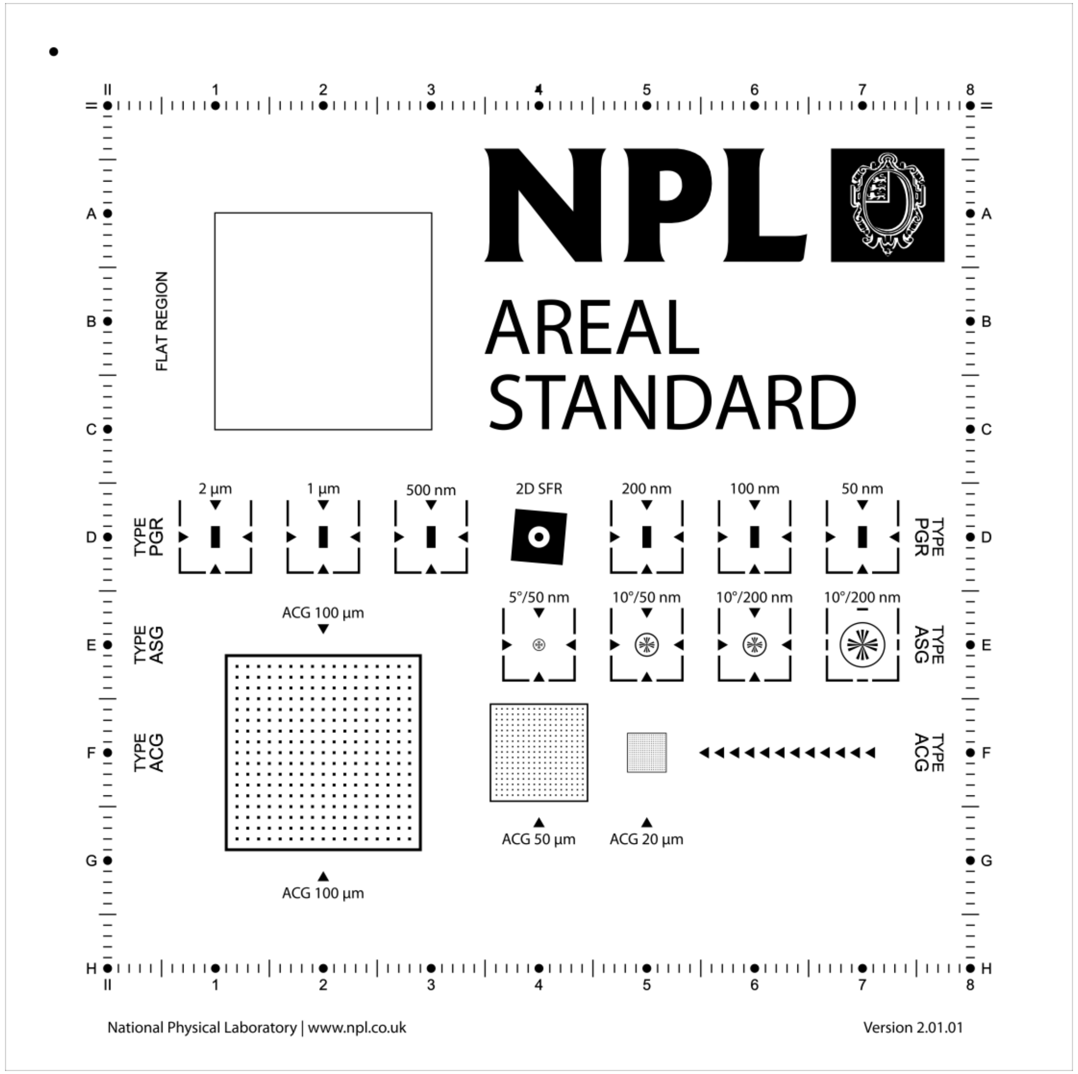
Objectives:

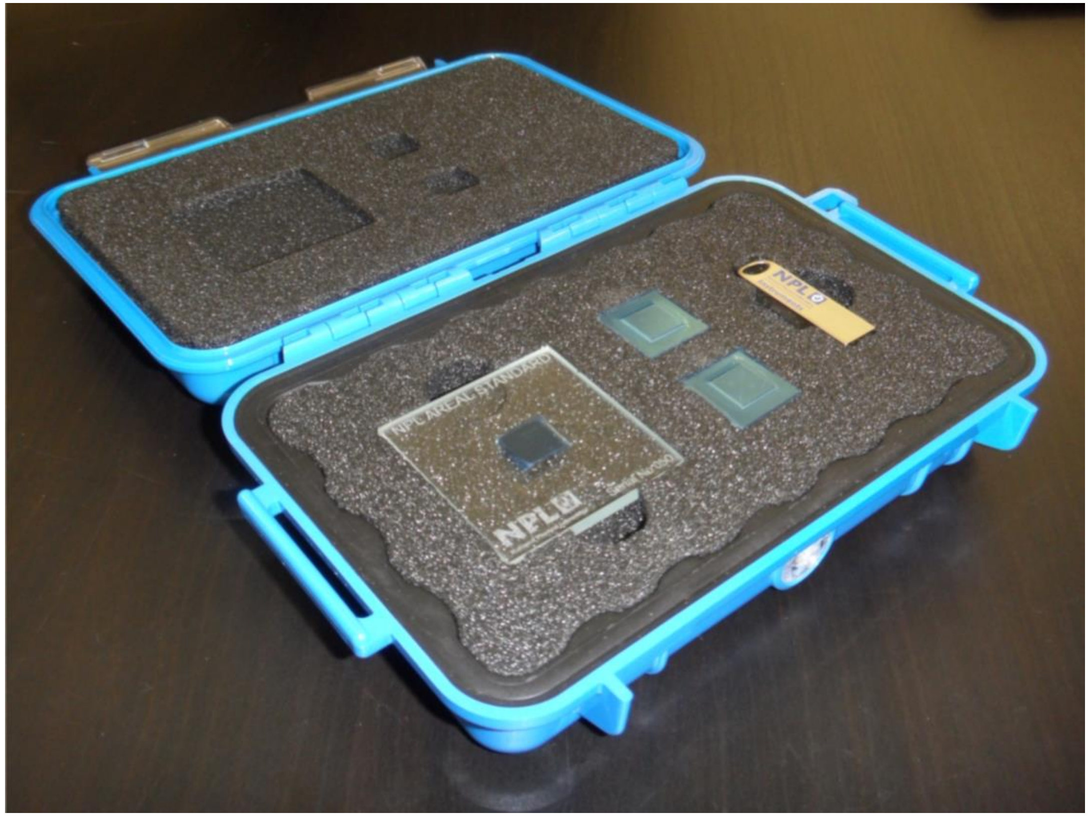
- To develop traceable and standardised methods for evaluating the uncertainty of coordinate measurement a posteriori using type A evaluation.
- To develop a simplified and validated method for predicting the uncertainty of coordinate measurements a priori using type B evaluation (i.e., expert judgement).
- To demonstrate the validity of existing methods and those from objectives 1 and 2 in industrial conditions and evaluate their consistency and accuracy against the Guide to the Expression of Uncertainty in Measurement (GUM) and its supplements.
- To contribute to revisions of EN ISO 15530 and EN ISO 14253-2 by providing the necessary data, methods, guidelines and recommendations, in a form that can be incorporated into the standards at the earliest opportunity.

- For more information see: http://eucom-empir.eu/

3D sensor calibration – NPL Areal Standard

-





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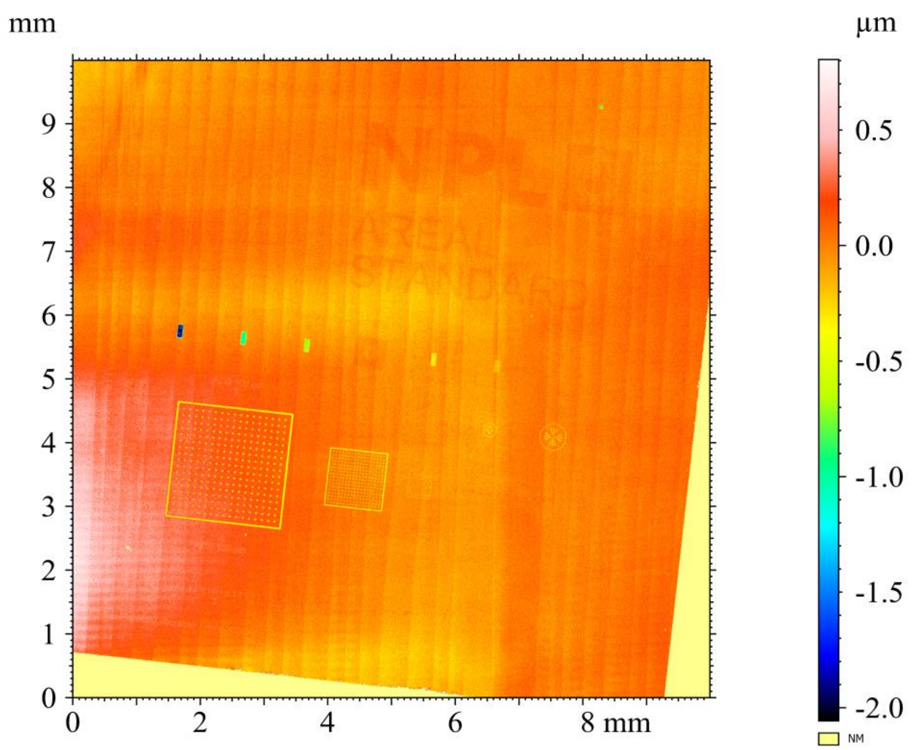
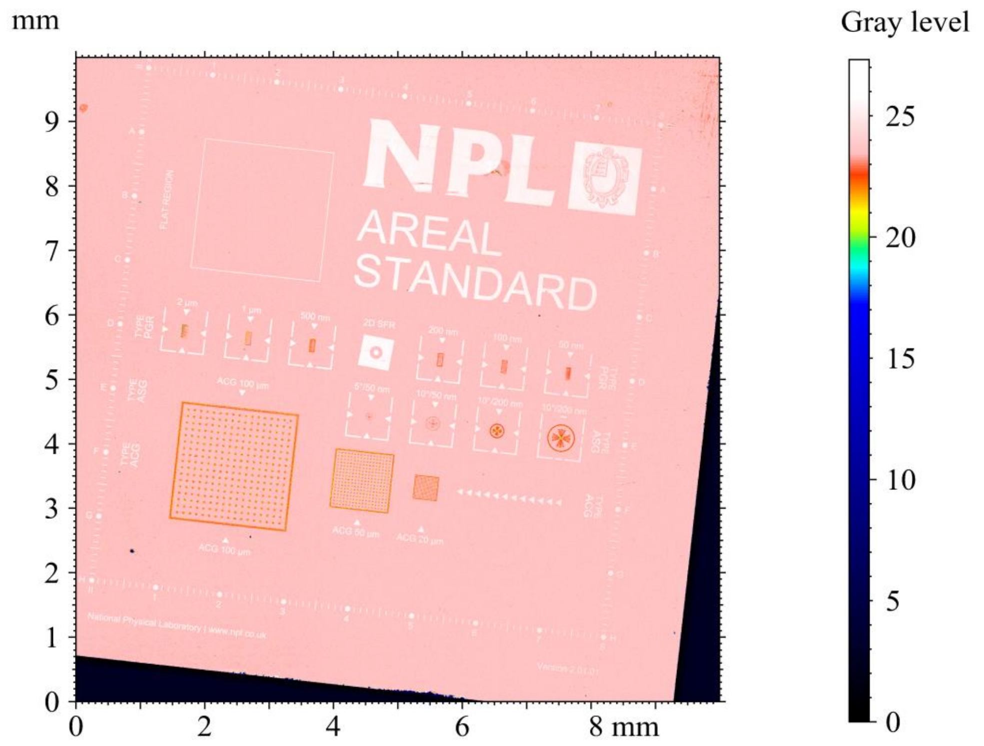


Areal height map

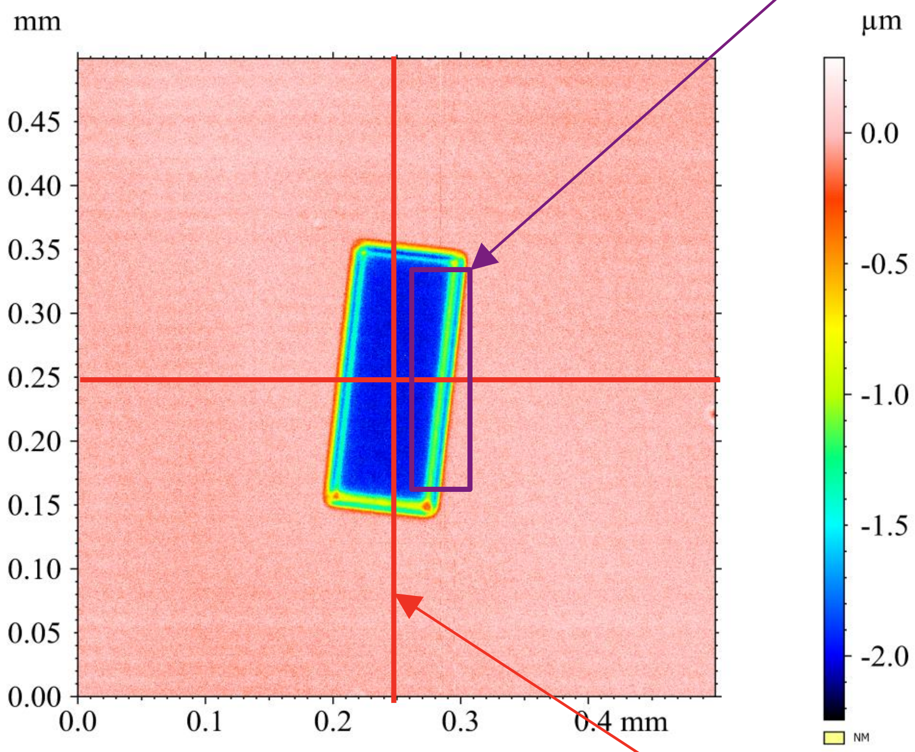


Confocal intensity map

3D sensor calibration – NPL Areal Standard

2 µm PGR
(step height)

Edge response: 3D resolution indicator



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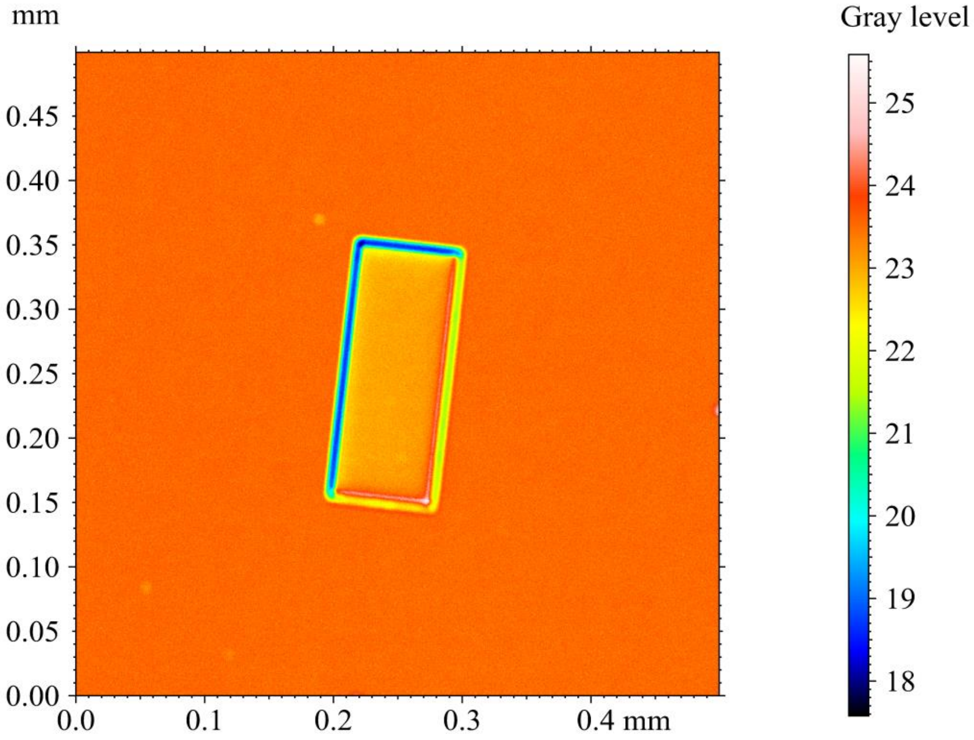

Confocal intensity map

Steps: xyz offsets

SI redefinition

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- Change in SI unit definitions for robustness and security
- Units defined in term of what appear to be universal and fundamental constants of nature
- Major changes for K and kg
(both relevant to precision engineering)
- No practical change for industrial metrology
- Comes into force 20 May 2019:
World Metrology Day

SI redefinition

Kilogram redefinition using Kibble balance

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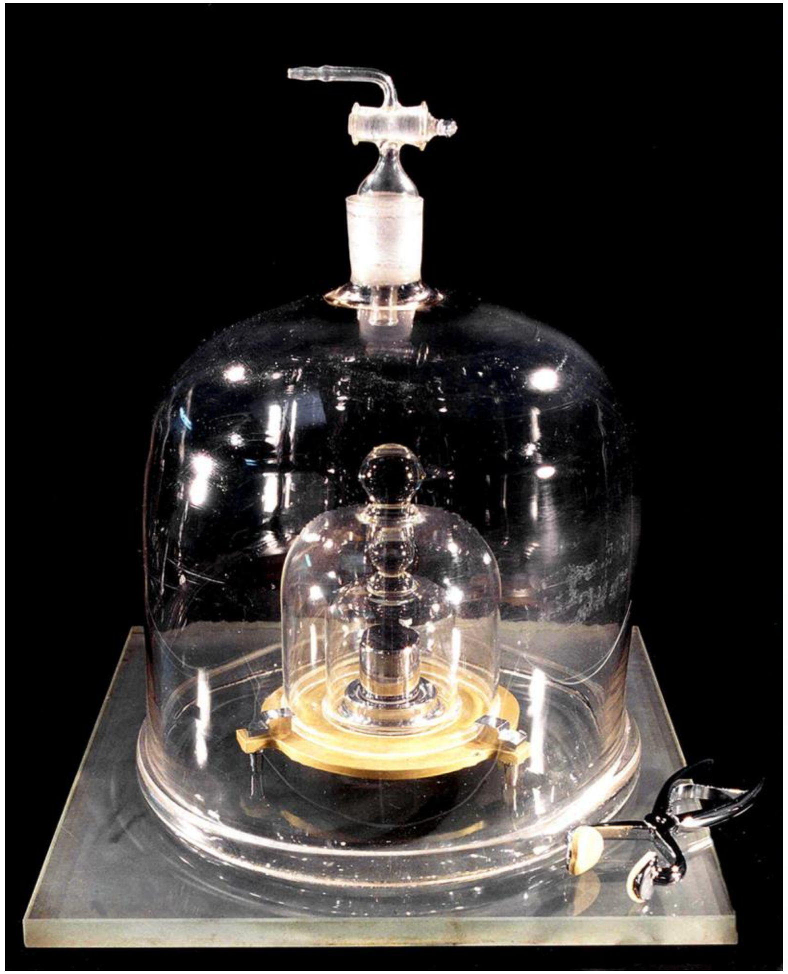

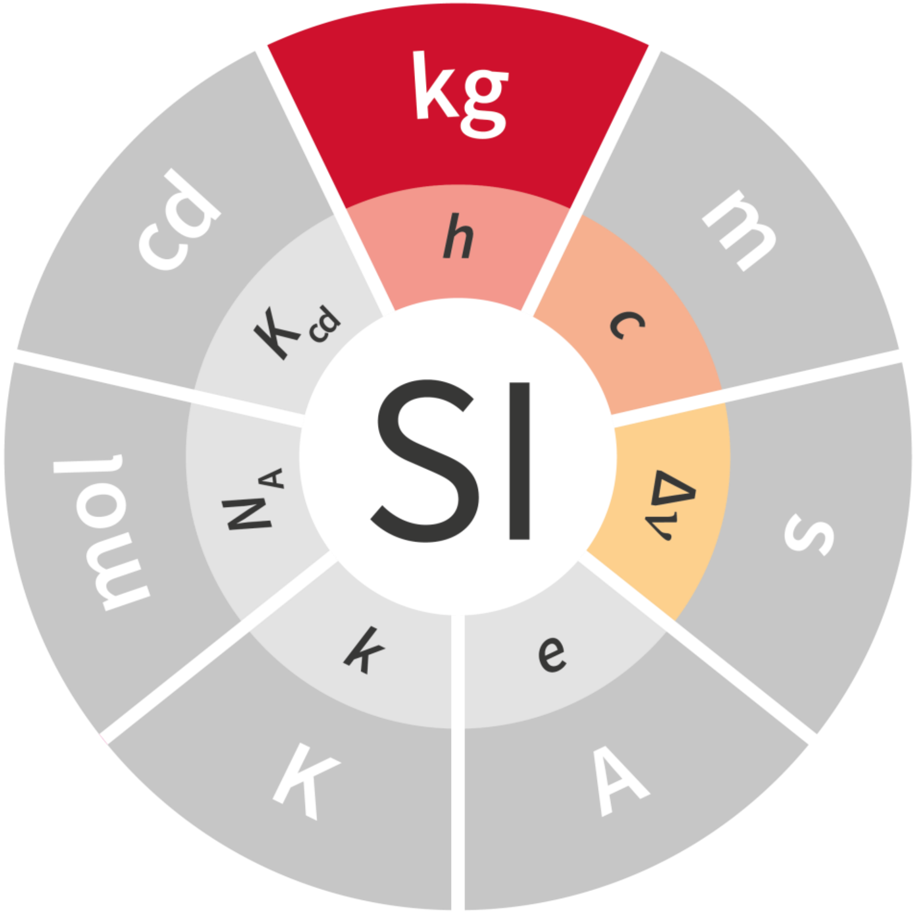

SI redefinition

Metre ‘redefinition’ – conceptual only

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“the speed of light in vacuum *c* is <u>exactly</u> 299 792 458 m/s”

“the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz”

metre defined