# Metrology for additive manufacturing

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www.nottingham.ac.uk/research/manufacturing-metrology

# What is today about?

- To inform the community about the research at Nottingham – including the results of recent reviews
- To highlight research at University of Huddersfield, NPL and MTC
- To get feedback on our approach

# The fellowship

- EPSRC Manufacturing Fellowship
- March 2015 to March 2020
- Total of £1.5m funding + leverage (£4.2m)
- Supports fellow (60%), 2 research fellows, equipment and impact activities
- Faculty support for 1 research fellow (2 years), 1 lecturer, 7 PhD students
- Letters of support from 5 academics, 3 research institutes and 14 industrials

# Partners - academic

Loughborough University

University of Huddersfield

Aston University

UNC Charlotte

1920 HIT

# Partners - industry

Nikon

TOYOTA

3T

RENISHAW
apply innovation™

ZEEKO Ltd

Lein
Applied Diagnostics

BRUKER

alicona

NEUTEQ™
Microfinishing & Robotic Automation

ZEISS

LOXHÅM
PRECISION

CALON
CARDIO

# Partners – national institutes

NPL National Physical Laboratory

Science & Technology Facilities Council

mtc Manufacturing Technology Centre

STFC Central Laser Facility

# Equipment and labs

- 2 main labs up and running (one temperature controlled), 1 lab being finalised, 1 lab due early 2016
- Alicona G5 focus variation microscope installed, Advanced Real3D ordered
- Nub3D fringe projection system installed
- Bruker Form & Texture (5 axis CSI) due February 2016
- Nikon XCT ordered for delivery February 2016
- HIT confocal microscope in proposal
- Also have access to stylus, chromatic confocal, 3 x CSI, CMM, micro-CMM, vision-CMMs, SEMs, AFM, dual-beam FIB
- Plus facilities in Nottingham Nanotechnology & Nanoscience Centre
- Full access to precision and additive machining facilities




# Plans

- Develop the next-generation of techniques for measuring complex form of AM parts
- Develop techniques for measuring surface texture of AM parts and move towards a mapping of process variables to texture
- Develop x-ray computed tomography for the measurement of internal form and texture of AM parts
- Develop in-process/in-line techniques for dimensional and defect measurement (existing work = OCT, SRAS, fringe projection, plastic & metal)
- Develop a calibration and performance verification infrastructure for the techniques above, including uncertainty estimation

# Early outputs

- Stavroulakis P, Leach R K 2016 Review of post-process optical form metrology for industrial-grade metal additive manufactured components *Rev. Sci. Instrum.* under review
- Everton S K, Hirsch M, Stavroulakis P, Leach R K, Clare A T 2016 Review of in-situ process monitoring and in-situ metrology for additive manufacturing *Materials and Design* under review
- Thompson A, Maskery I, Leach R K 2016 X-ray computed tomography for additive manufacture: a review *Meas. Sci. Technol.* to be submitted by Christmas
- Townsend A, Senin N, Blunt L A, Leach R K, Taylor J 2016 Review of surface texture measurement for additive manufacturing, to be submitted by Christmas

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# How can you engage?

- Support PhD research (so far NPL, MTC, 3T RPD, Nikon, Bruker, RAL, Alicona)
- Support research fellows
- Supply equipment
- Allow access to equipment (metrology and manufacturing)
- Industrial internships, including KTPs
- Feedback metrology requirements
- Provide case studies (especially components to be measured or in-line scenarios)
- Get involved in the research (especially towards joint publications)

# Agenda

| | |
|---|---|
| 10:00-10:20 | Arrival and coffee |
| 10:20-10:30 | Introduction and purpose of the meeting *(Richard Leach)* |
| 10:30-11:00 | The UK Strategy for AM *(Phill Dickens)* |
| 11:00-11:30 | Introduction to AM metrology at Nottingham *(Richard Leach)* |
| 11:30-12:00 | Co-ordinate metrology for AM *(Petros Stavroulakis)* |
| 12:00-13:00 | Lunch |
| 13:00-13:30 | Surface texture measurement for AM *(Nicola Senin, Andrew Townsend)* |
| 13:30-14:00 | AM metrology at NPL *(Stephen Brown)* |
| 14:00-14:30 | Internal feature metrology for AM *(Adam Thompson)* |
| 14:30-15:00 | In-process metrology for AM *(Sarah Everton, Ben Dutton)* |
| 15:00-15:20 | Coffee break |
| 15:20-15:40 | Open forum |
| 15:40-16:00 | Tour of MTC AM and metrology facilities |

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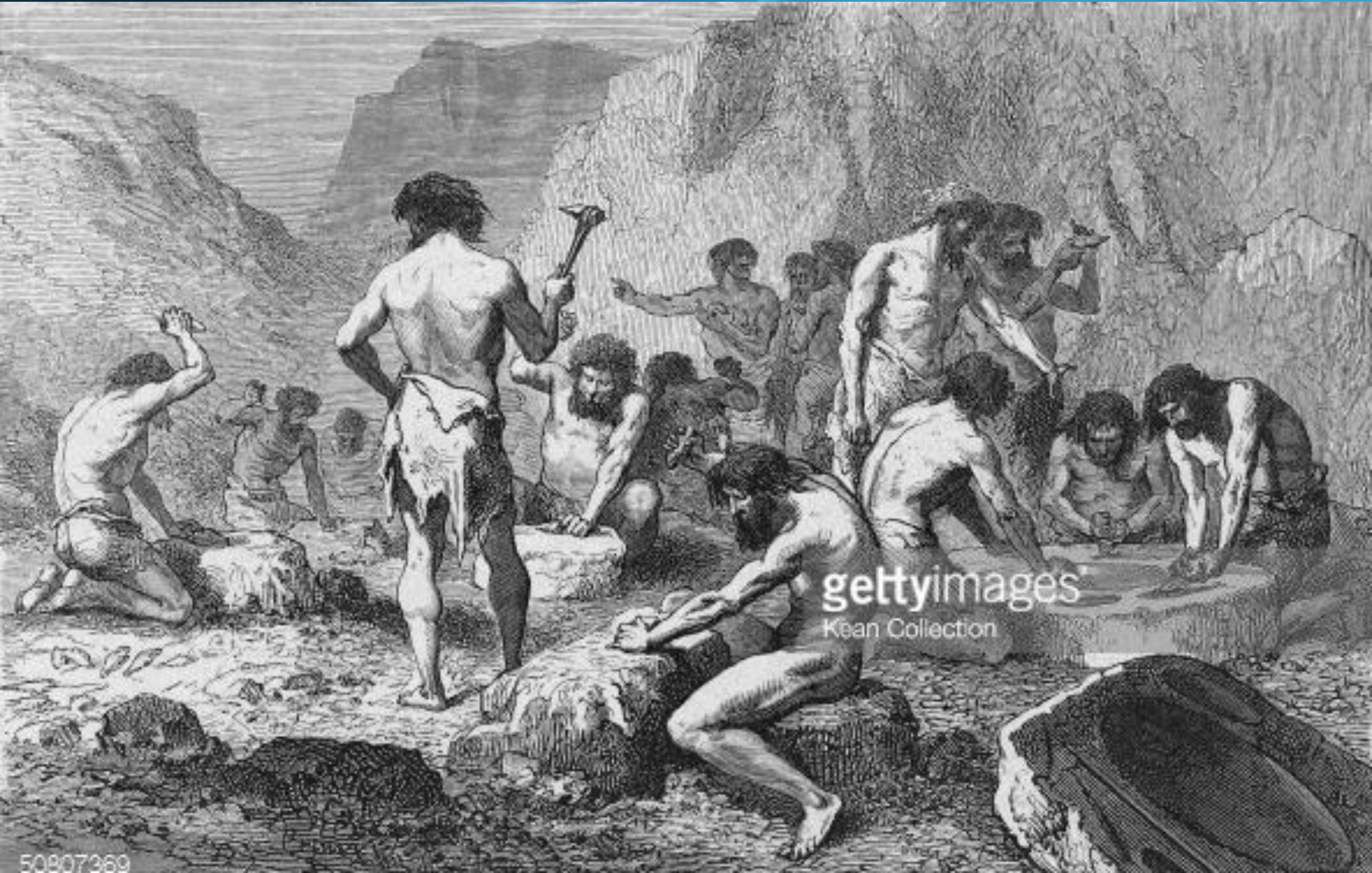
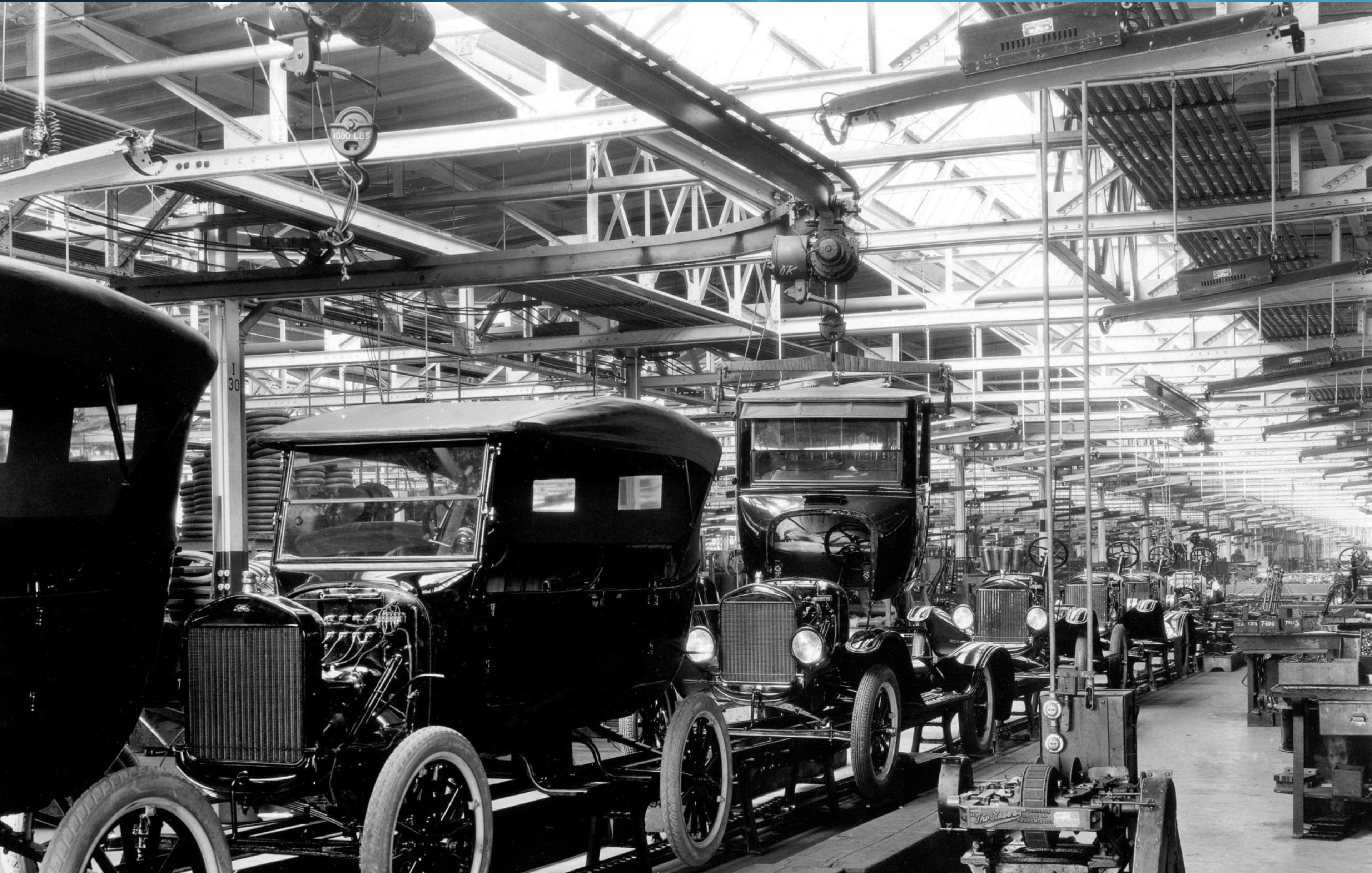
# An apology…

# Additive Manufacturing

# Manufacturing – Phase 1



# Manufacturing – Phase 2



# Manufacturing – Phase 3?

# Why all the interest?

1. Enabler for **LOW VOLUME** production
2. Maximising **DESIGN COMPLEXITY**
   - Key enabler
3. Additional **FUNCTIONALITY**
   - Single and multi-material
4. Customisation and **PERSONALISTION**
5. **BUSINESS REORIENTATION**
   - new business models, **SUPPLY CHAINS, LOGISTICS**
6. Potential **ENVIRONMENTAL** benefit
   - Very application dependent

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# Metrology

# Something missing?

- With AM we can make some highly-complex components and even assemblies
- But what about QUALITY?
- So far, most people involved in AM have never heard of the word TOLERANCE
- All mature production processes have suitable quality systems in place
- Why should this be different for AM?

# Why measure?

- To know whether a part is fit-for-purpose – tolerances and functionality
- To allow assembly of complex components
- To allow control of a manufacturing process
- To avoid unnecessary scrap material and redundant processing time - cost, environment
- To improve energy-efficiency
- To give "customers" confidence in a product

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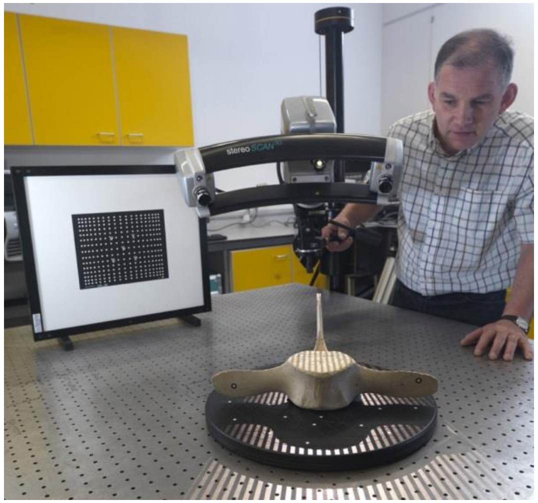
# Metrology for Additive Manufacturing

# Current metrology in manufacturing

- Contact co-ordinate measuring machines (CMMs)
- Very common in modern manufacturing industry
- Accurate but slow


- Optical co-ordinate measuring machines
- Becoming more popular
- Fast but inaccurate

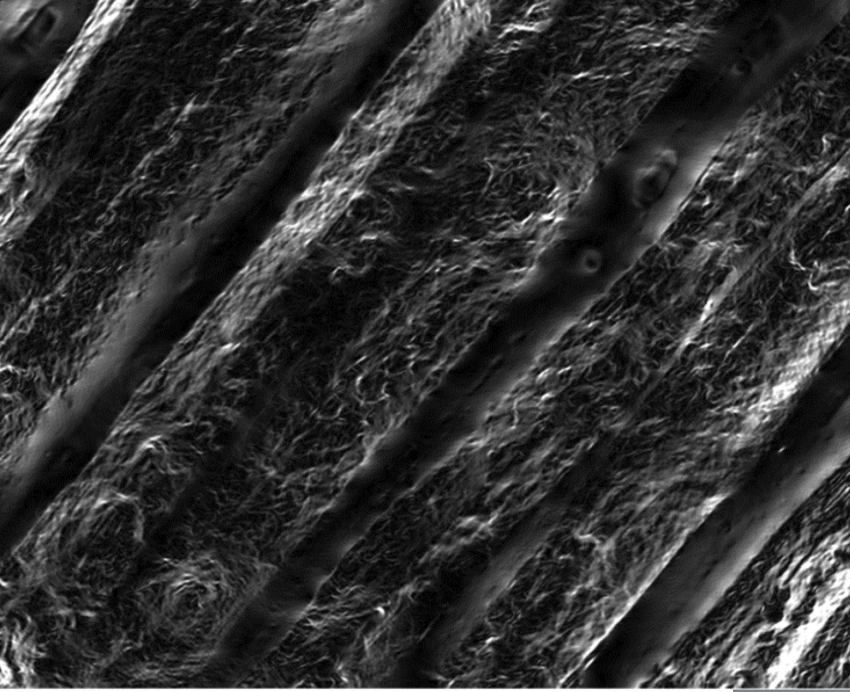


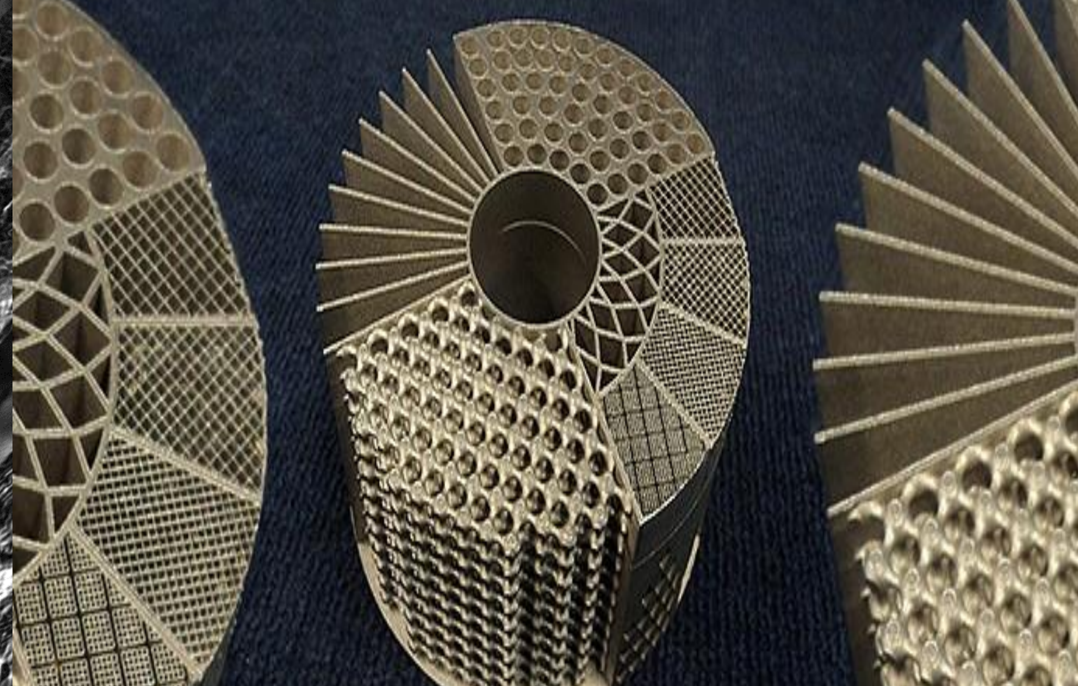
- X-ray co-ordinate measuring machines
- New kid on the block
- Holistic: external and internal
- Accuracy questionable

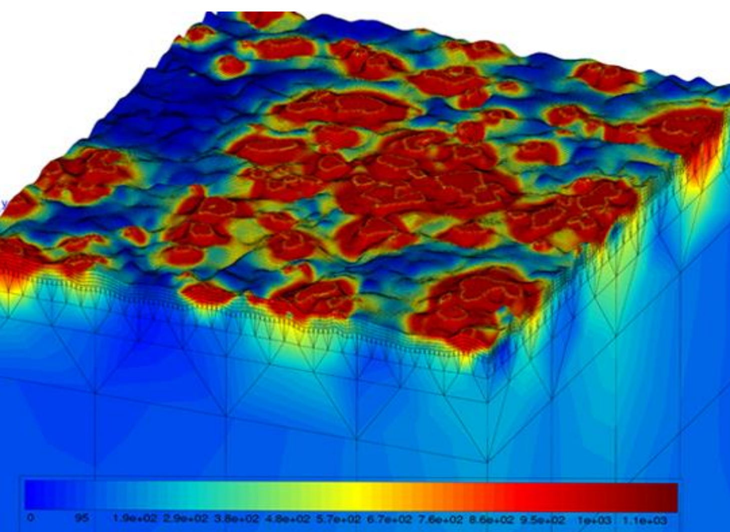
# State-of-the-art in dimensional measurement for AM

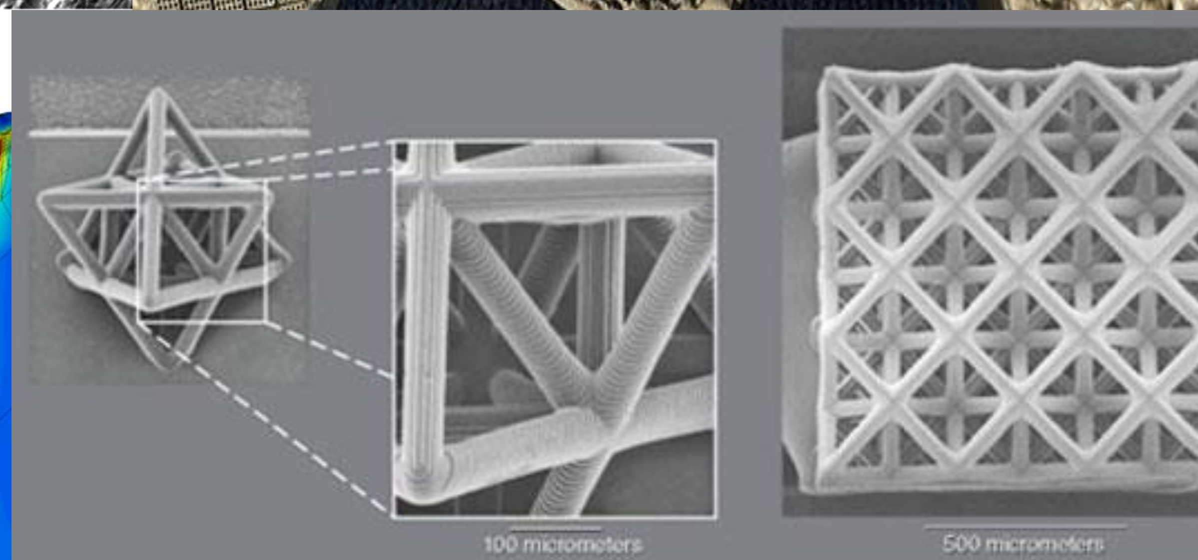
- Form: contact CMMs, fringe projection, laser triangulation – slow, lack of access, difficult in-process
- Texture: contact, optical – slow, difficult surfaces – see later
- Internal features: X-ray CT – expensive, slow, difficult in-process
- Defects in-process: thermal cameras, imaging systems – limited information content (not 3D), little tolerance information

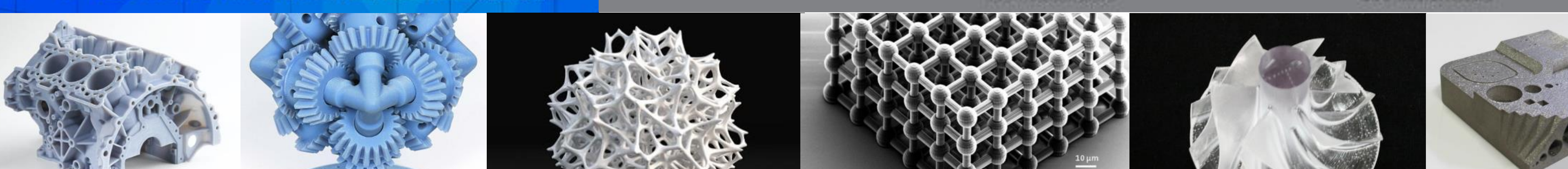
# Why is AM an issue for metrology?






0 95 1.9e+02 2.9e+02 3.8e+02 4.8e+02 5.7e+02 6.7e+02 7.6e+02 8.6e+02 9.5e+02 1e+03 1.1e+03


100 micrometers
500 micrometers

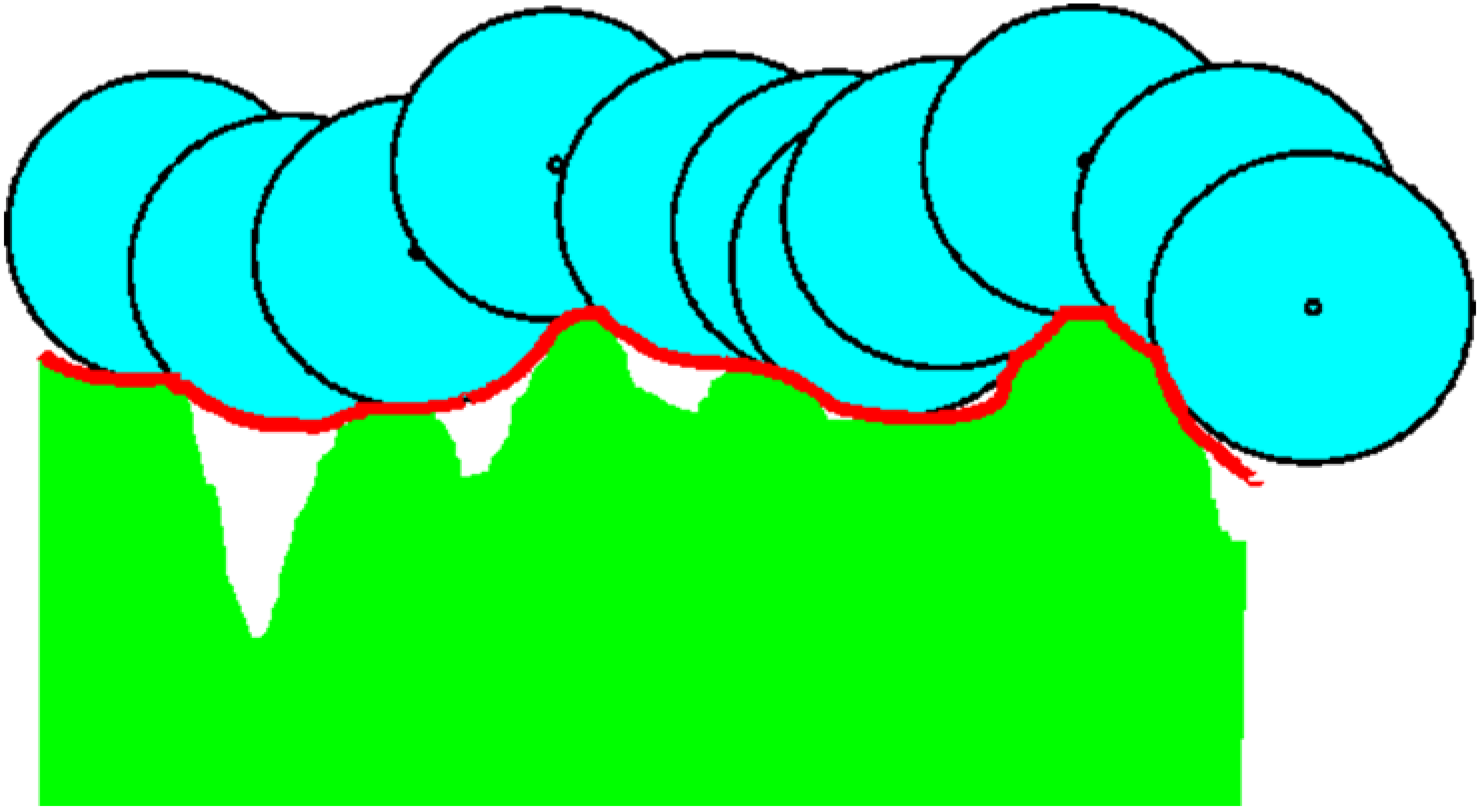

10 µm

# Why is AM an issue for metrology?

- With almost infinite design freedom, comes almost infinitely complex shapes to measure!
- Complex surface texture – very high slope angles
- Huge range of materials – plastics, metals, ceramics, … growing daily
- The need for speed!

# Back to Basics

# Surface measurement – all about spatial frequencies



The "mechanical surface": analytical solutions

# Why use optical and not contact?

- Contact always causes damage, although this is often over-emphasised
- Optical can be much faster – in-line solutions become practical
- For coordinate metrology, optical systems give a large set of point cloud data rather than a few carefully-chosen points
- Optical instruments can be easier to use – this is a critical point – see next slide

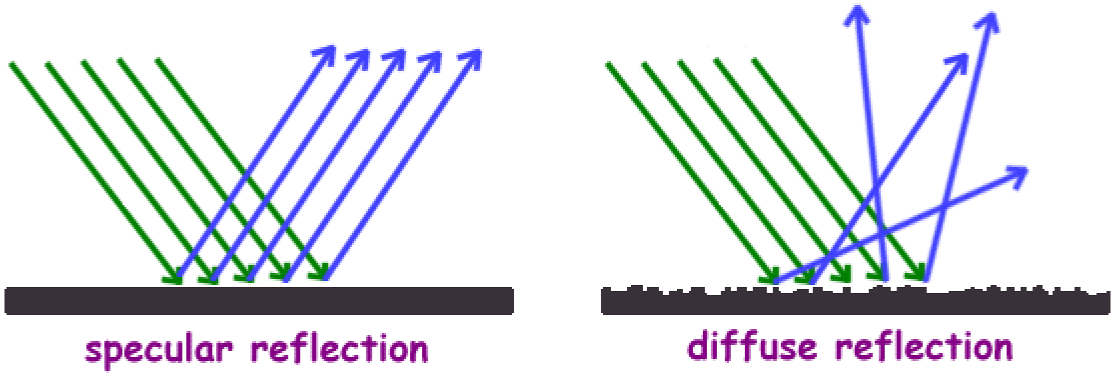
# Why use optical and not contact?

- Work of art piece of precision engineering
- But
  - Difficult to use
  - Fragile, easily broken
  - Lack of access
  - Expensive, to buy and to maintain

F25 micro-CMM at Nottingham and NPL

# Optical instruments - basics

- Light reflected from a surface and the returned amplitude (and phase) data interrogated
- Can vary depending on:
  - Incident angle (spatial bandwidth)
  - Source spectrum (temporal bandwidth)
  - Degree of coherence
  - Polarisation state

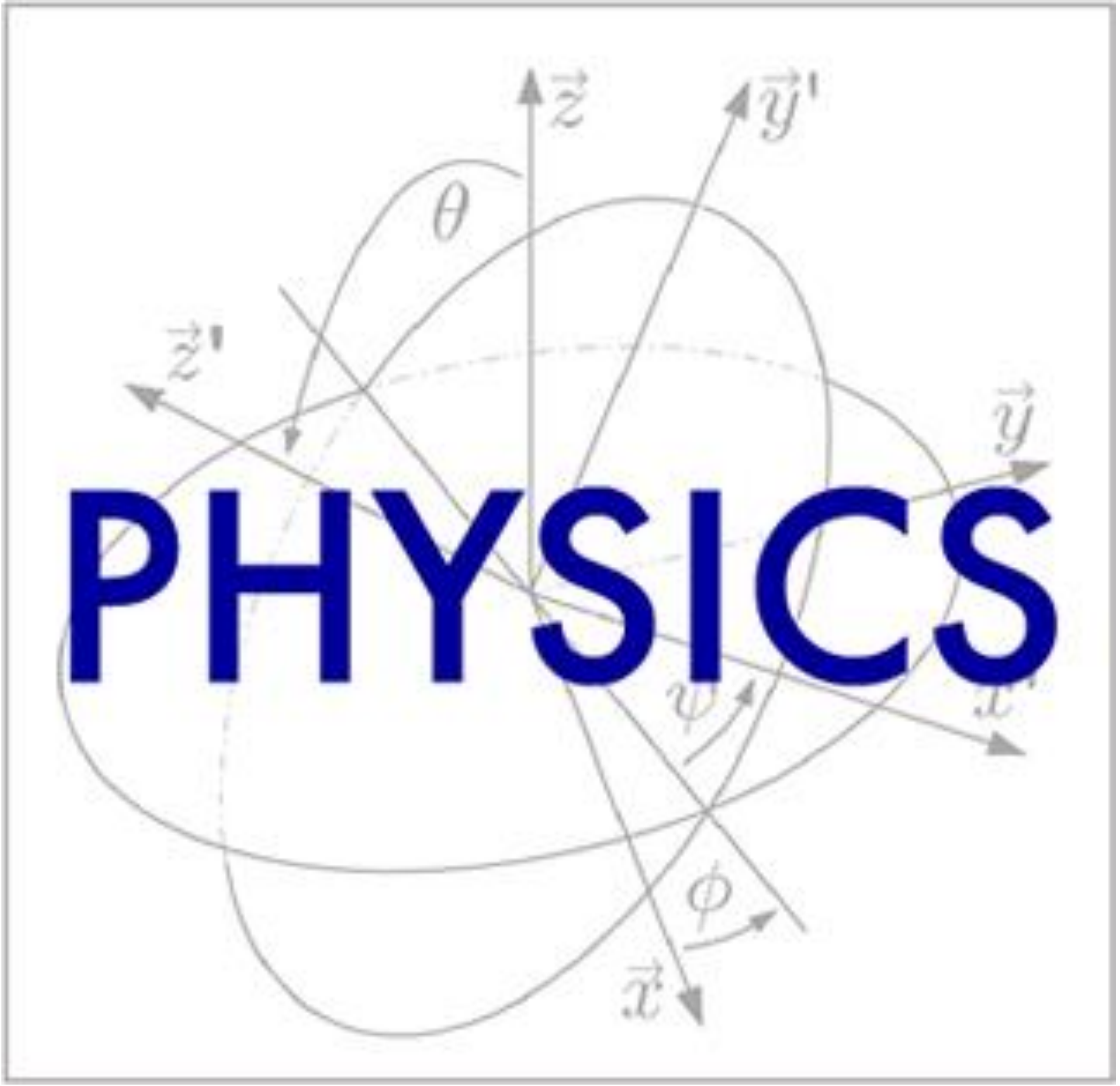


# Optical instruments - limitations

- Finite spatial frequency bandwidth due to diffraction limit and/or pixel size/density
- Finite range due to imaging and detection apertures
- Slope limitation due to finite angular collection system
- Aberrations in the optics leading to “optical artefacts” – these are often due to non-linear affects and difficult to predict and/or correct
- Speed issues due to need for scanning (mechanical or wavelength)
- Big data!
- Lack of standardisation
- ….

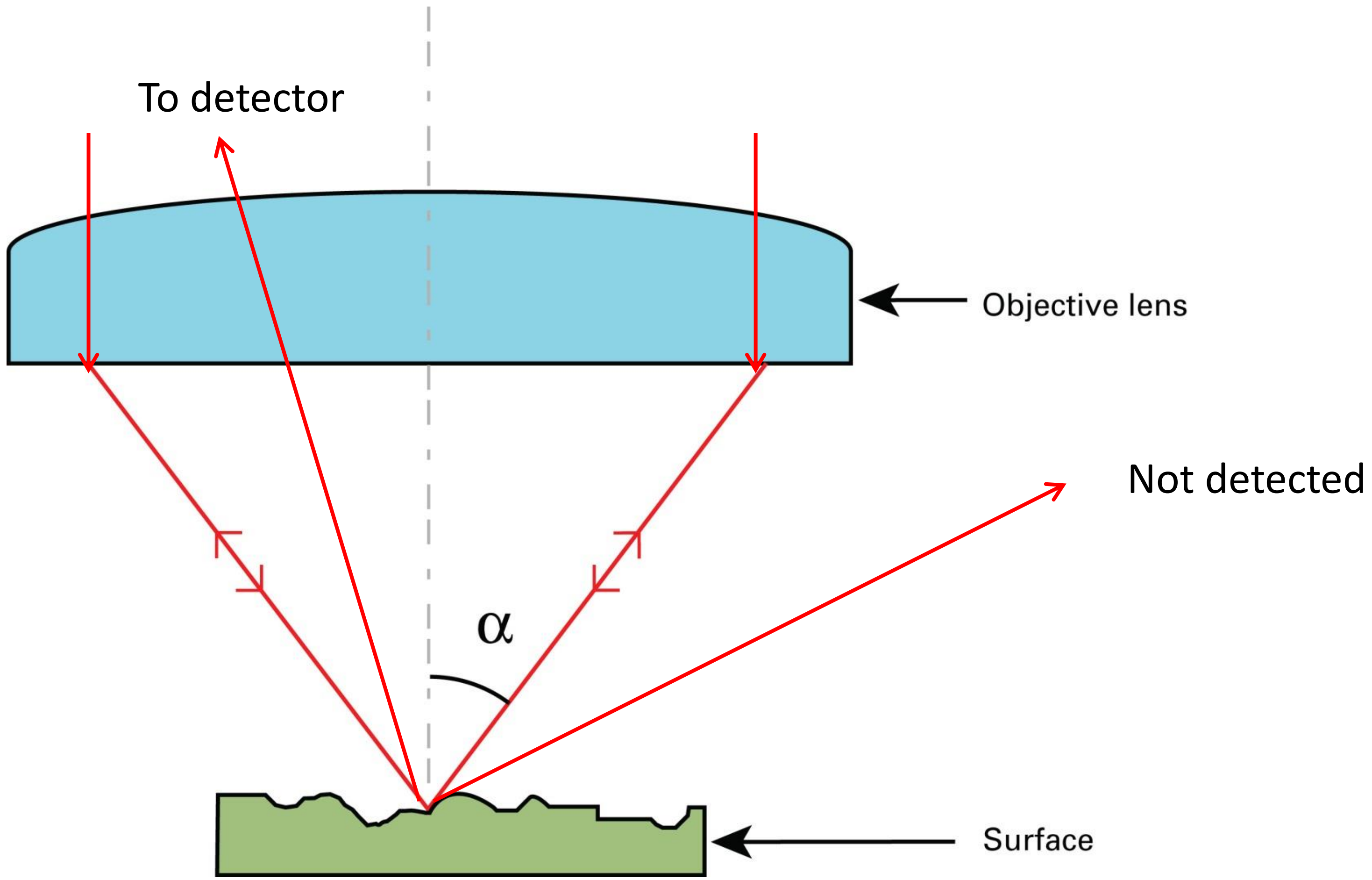
# So why can't we stride forward?

# So why can’t we stride forward?

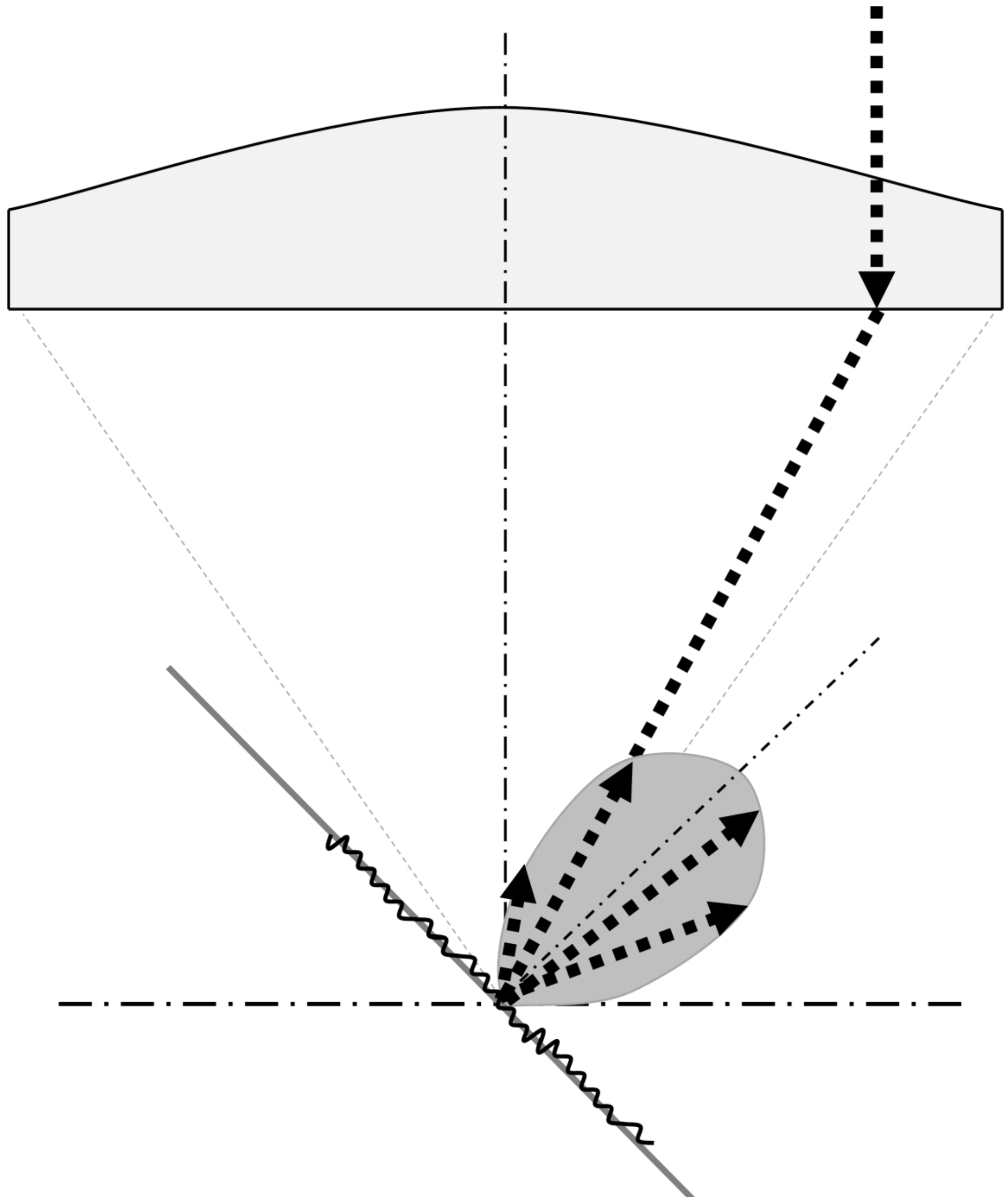


# … and

# Numerical aperture – slope limitation



# Numerical aperture – slope limitation



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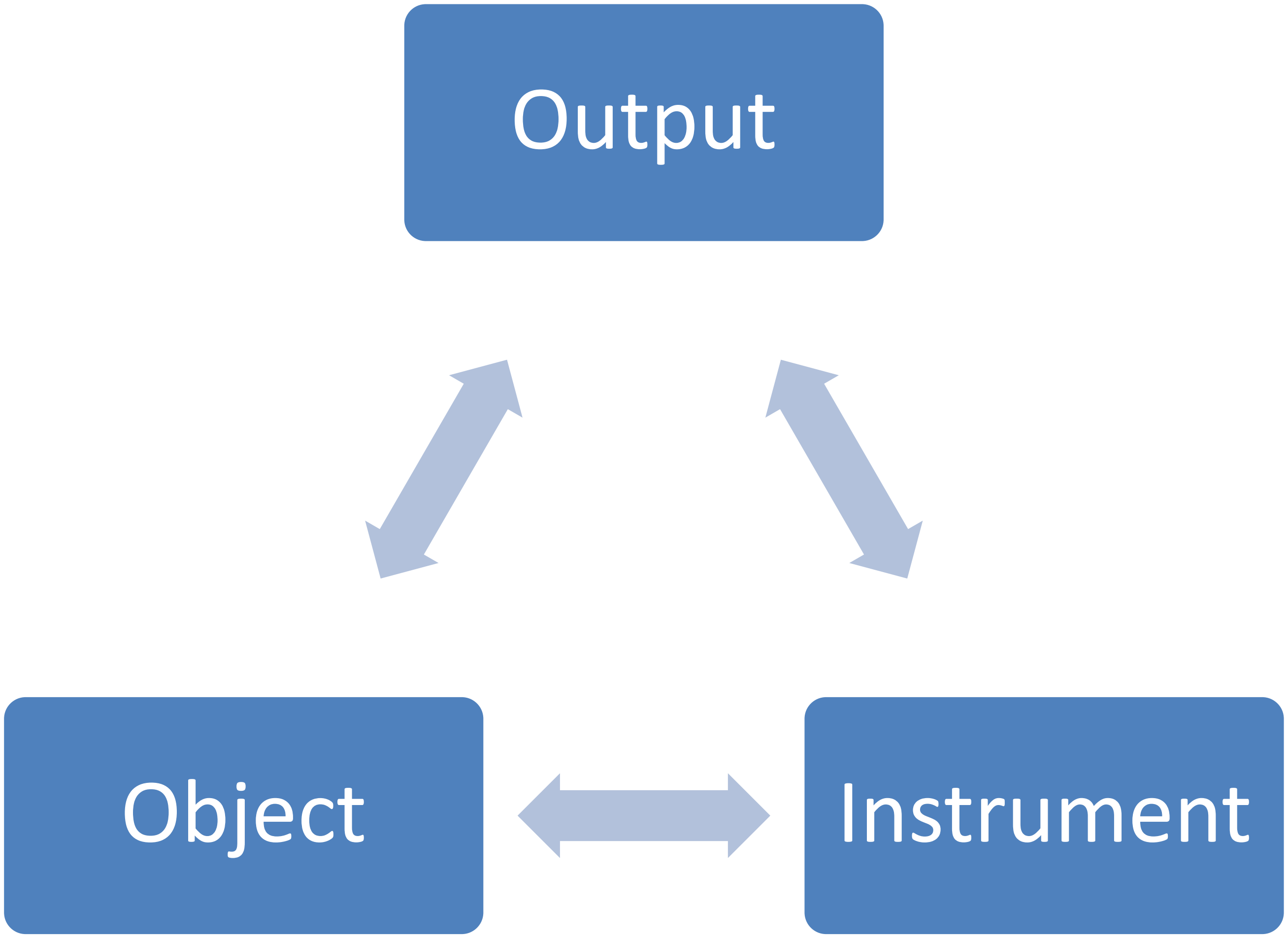
# Information-rich Metrology

# Can we do anything about these issues?



# "Information-rich metrology" (IRM)

IRM = Rigorous models of the instrument-surface interaction, often including all the nasty non-linear parts + Information about the object being measured, *e.g.* CAD data, course measurements, manufacturing specifications, …

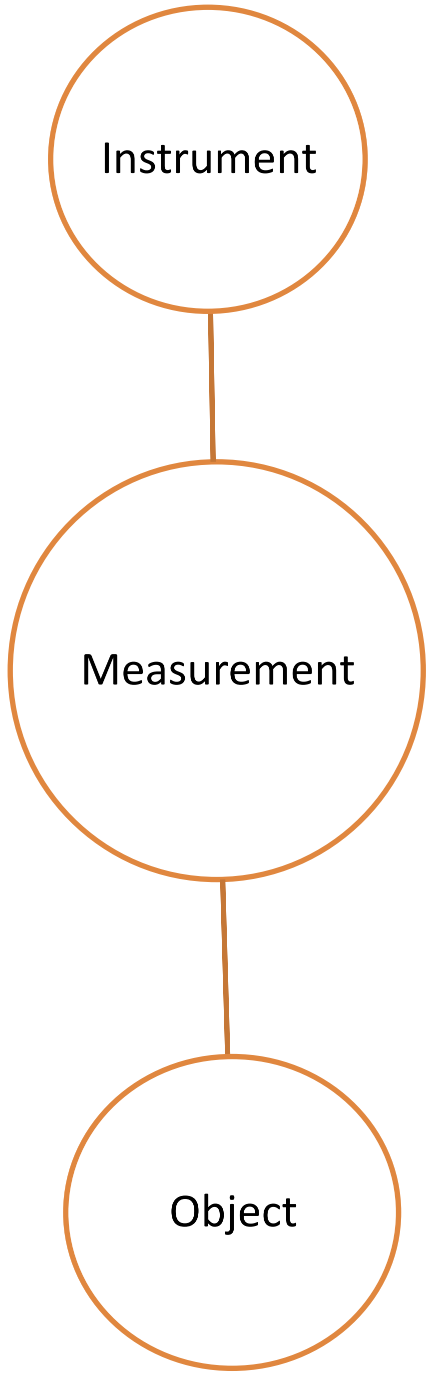
# New paradigm: Information-rich metrology (IRM)

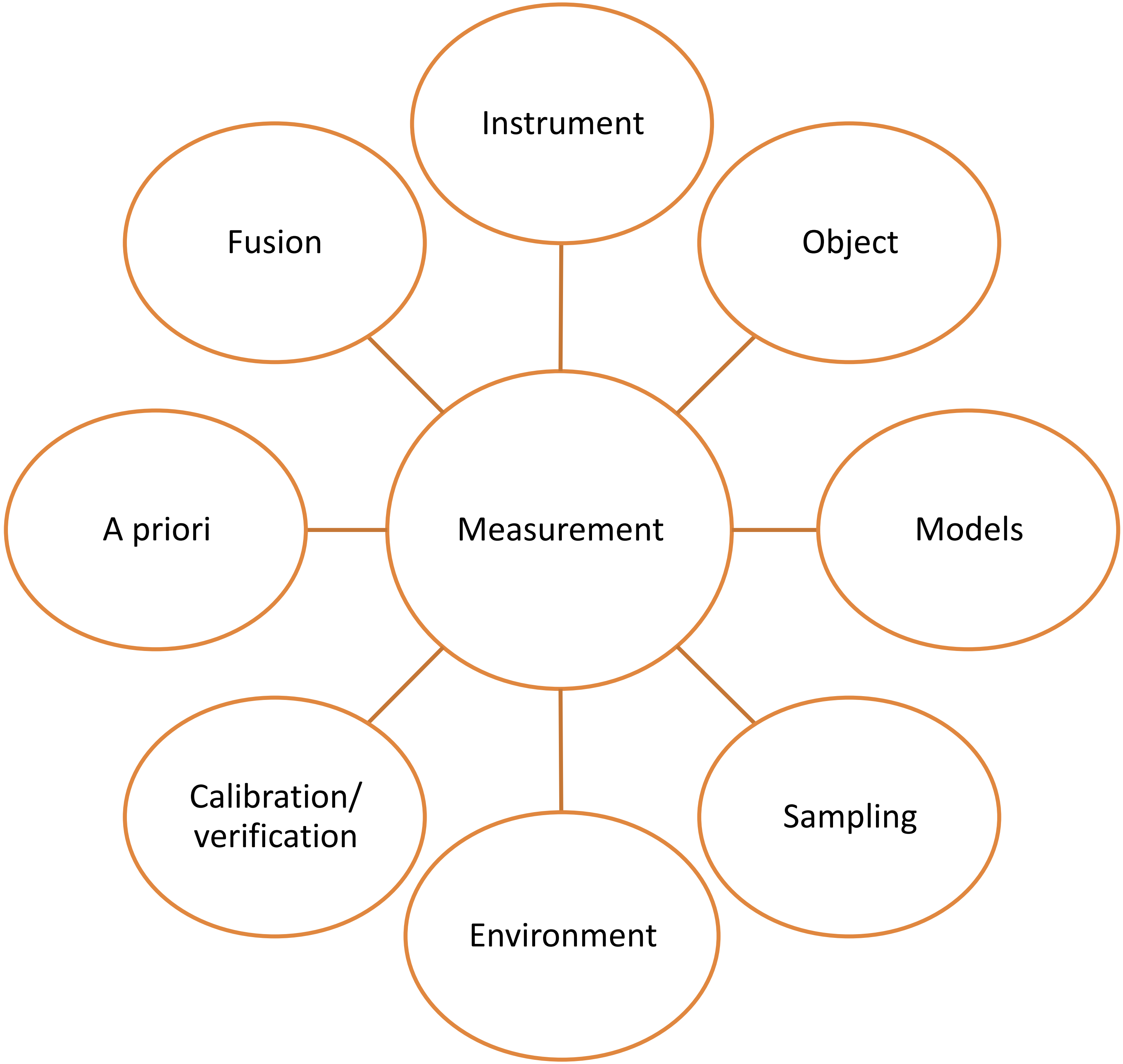
- Exploit all *a priori* information (*e.g.* CAD, models, course measurement data, *etc.*)
- Use of probe and measurand modelling

  -> increase measurement bandwidth

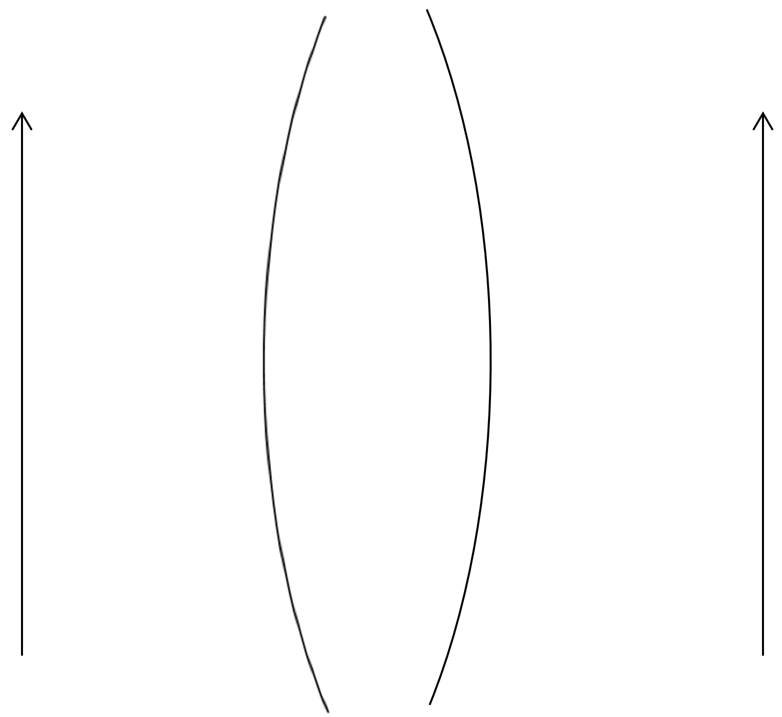
  -> decrease measurement times/information content
- Akin to super-resolution techniques

Optical instrument + ***A priori* information** / **A good model** = Result with higher bandwidth

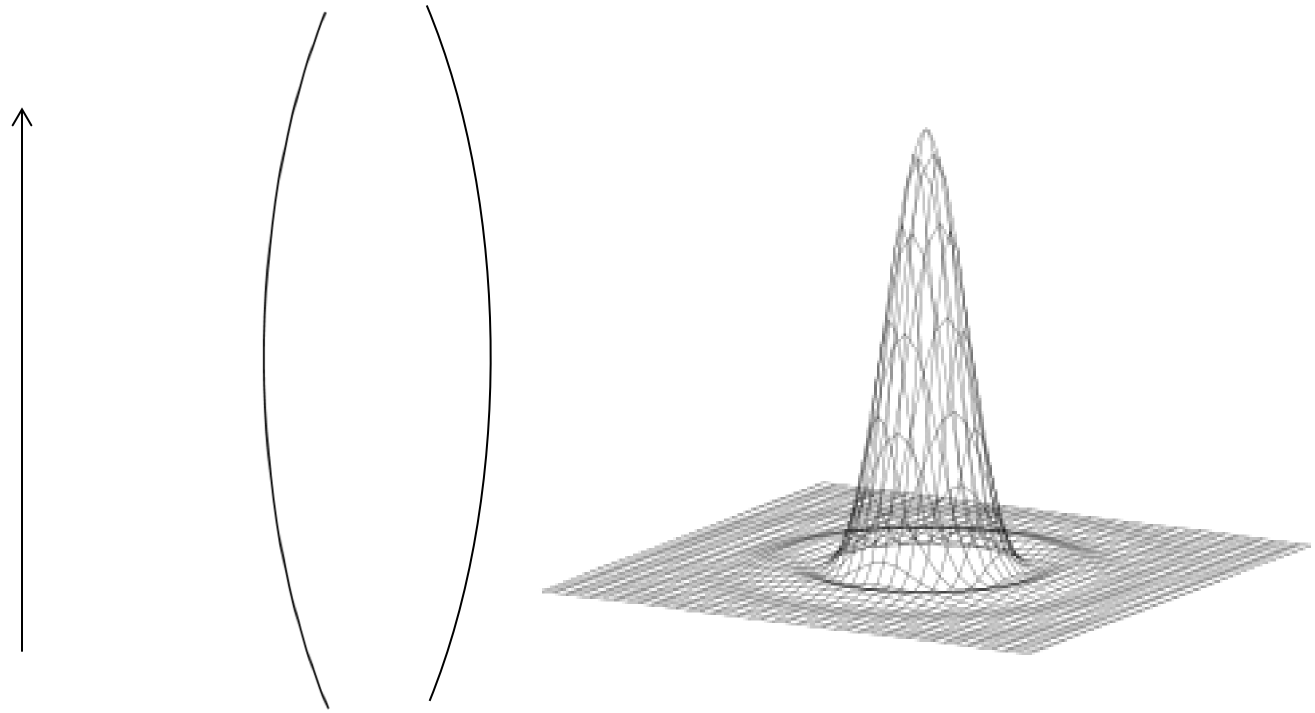

Instrument
Measurement
Object


Instrument
Fusion
Object
A priori
Measurement
Models
Calibration/
verification
Sampling
Environment

# The imaging process



# The imaging process



# What about high slopes?

- Nice linear theory only works for surfaces with slopes within the spatial bandwidth (aperture limit)
- What about slopes outside this limit?
- The linear filtering model no longer applies in this case because of multiple reflections
- But, with Loughborough University, we are developing a rigorous model which seems to be able to correctly predict results from various instruments
- Computational speed is the issue rather than physics…

# Inverse problem

We know we can produce outputs that show the surface related problems of instruments to solve *the forward problem.*

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

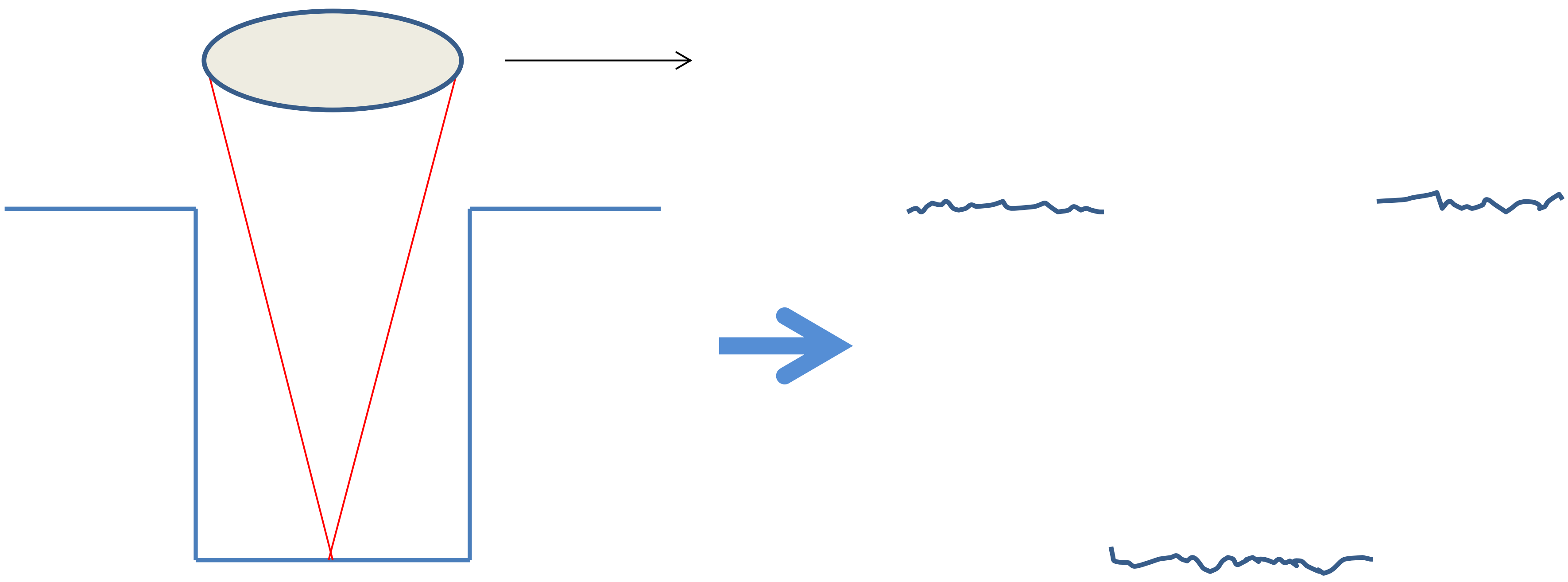
This is *the inverse problem*. Mathematically it is the solution that minimises an error function such as,

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

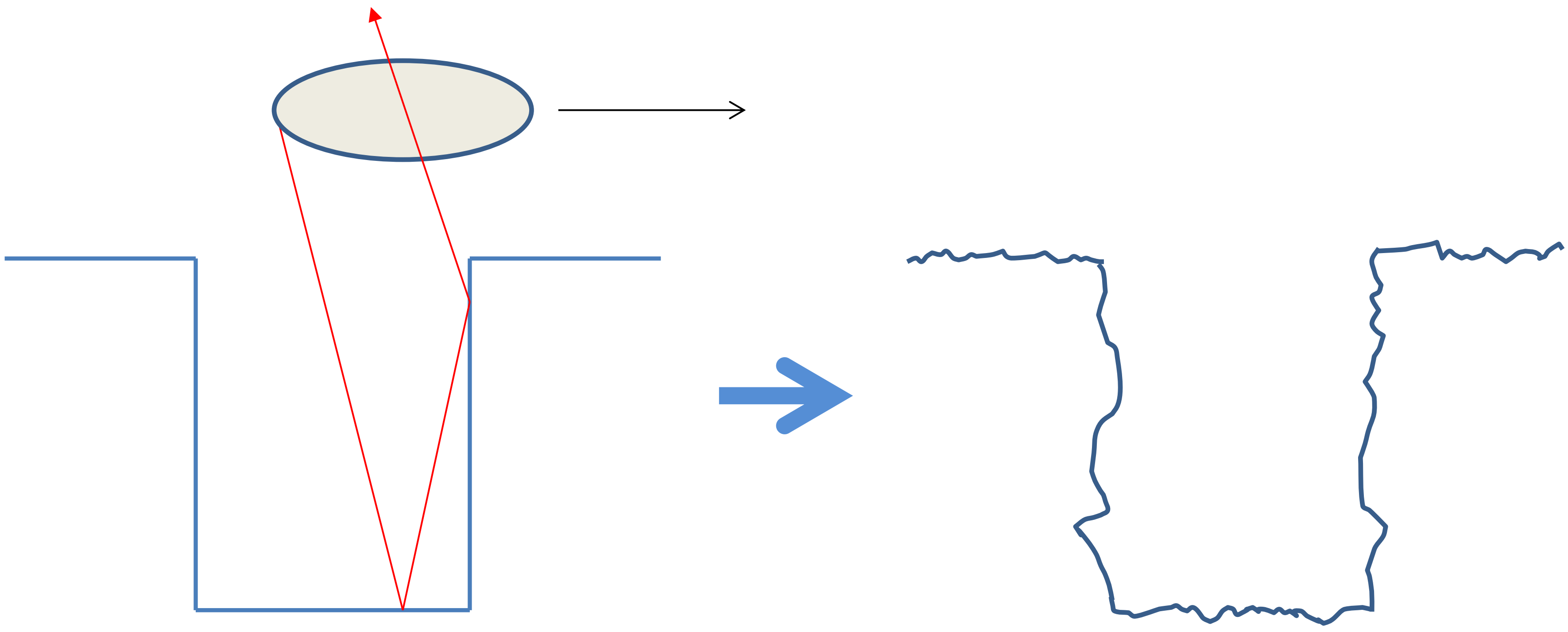
Measured scattered field — Calculated scattered field

A. Sometimes!

# What about high slopes?

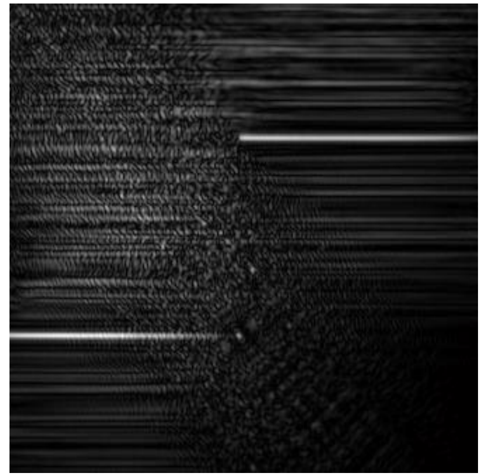


# What about high slopes?



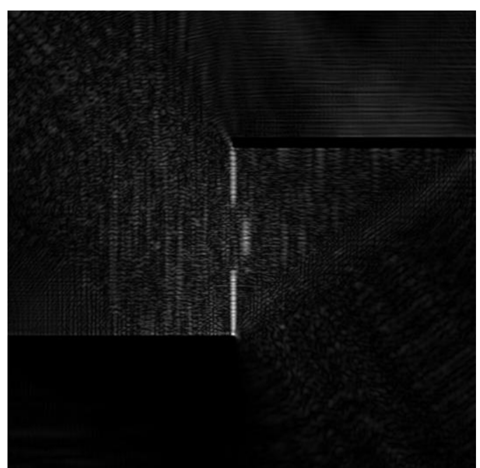
# Optical trickery?

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



CSI results: top and bottom surfaces are found

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



# Conclusions

# "It's never too late to start over!"

- The use of *a priori* manufacturing data gives us a wealth of information to exploit
- Combine this with rigorous modelling and we can significantly enhance measurements
- Often this involves non-linear optimization and 3D solvers -> need to look at fast approaches
- IRM will form the focus to build a world-leading, game-changing team at Nottingham

# Manufacturing Metrology Team

# Open forum

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# Questions

- Are we taking the right approach?
- Have we got the appropriate team and partners?
- Have we missed anything critical?
- What about the materials metrology?
- Is the UK appropriately embedded in the standards infrastructure?
- Should we do something like this regularly? If yes, how regularly?

# Manufacturing Metrology Team