Additive Manufacture Challenge Workshop

Advanced Manufacture of Optical Components

3D Printed Mirrors

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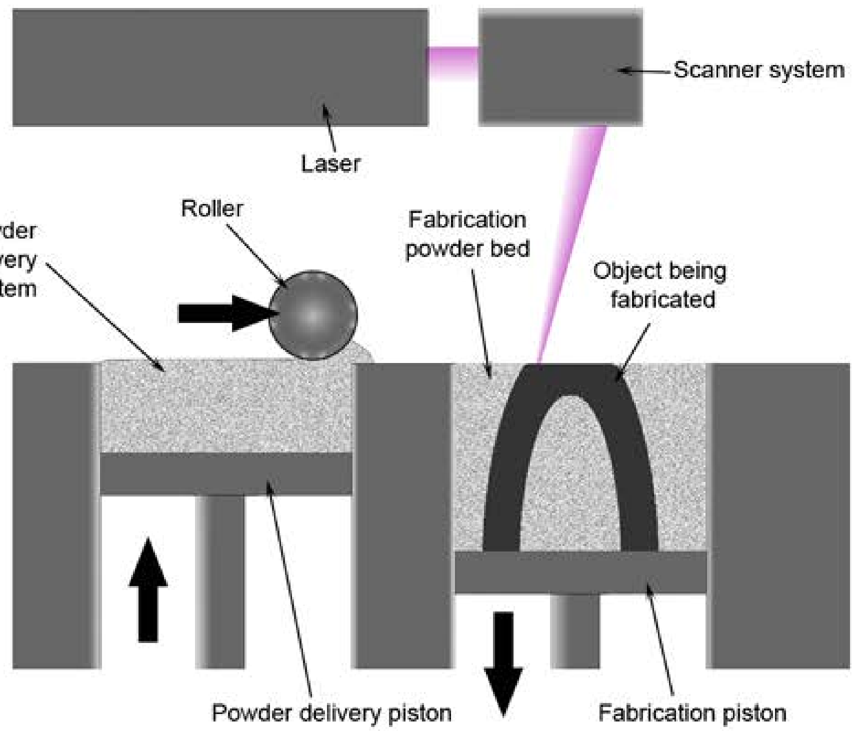
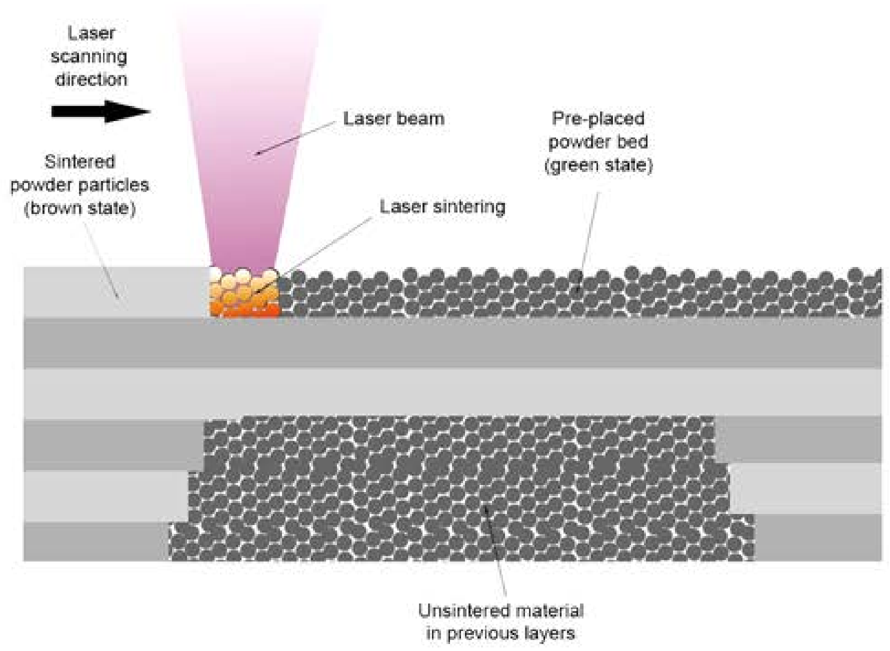
Selective Laser Sintering Principle

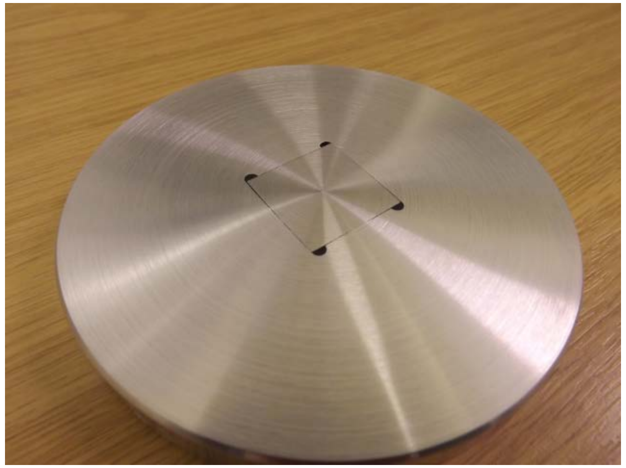
- Direct or Selective laser sintering varies in the detail of 'melting' the powder or sintering it. The principles are broadly speaking the same. We have selected DMLS (UK supplier)





Advanced Manufacturing Techniques for Optical Components

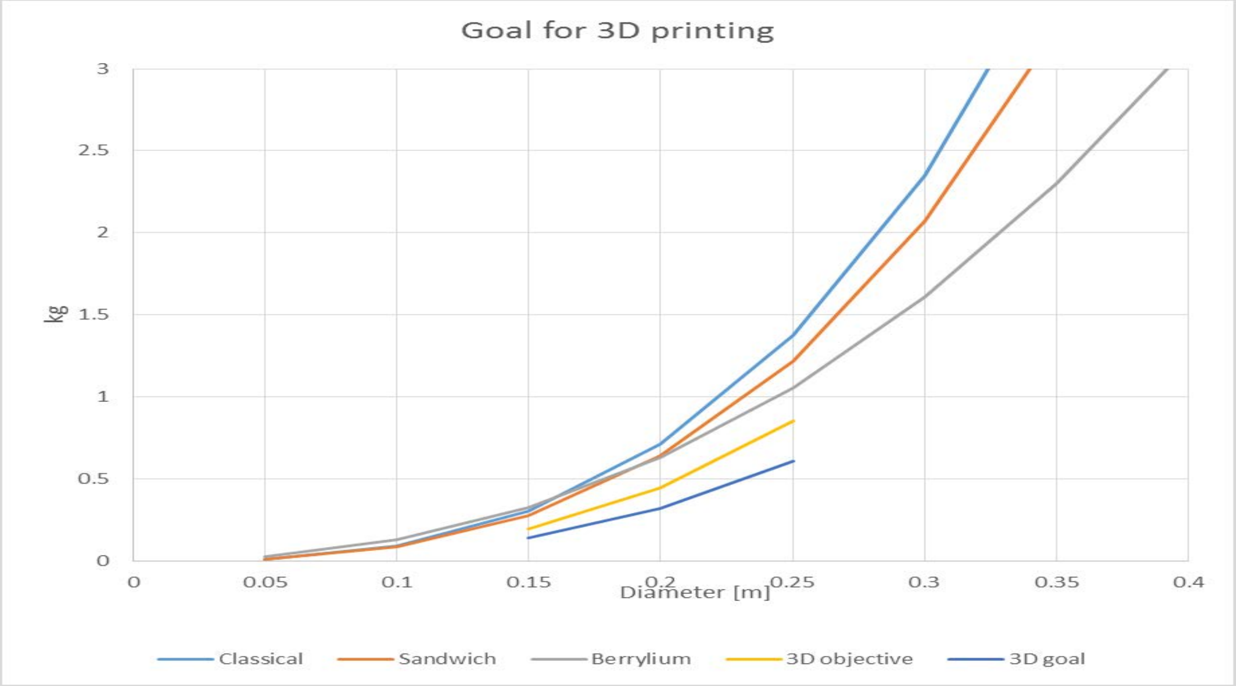
- In March 2015 we started the project to assess the options regarding printing mirror blanks using direct metal laser sintering printing
  - The project is funded by CEOI-ST based in the UK
- Focus was on type of metal (limited scope due available budget)
  - Titanium
  - Aluminium
- Print simple solid test samples and assess porosity
  - We selected two different suppliers
  - Samples arrived and were cut back for sample holder
  - Samples were ground and polished at OSL



Light Weight Optics

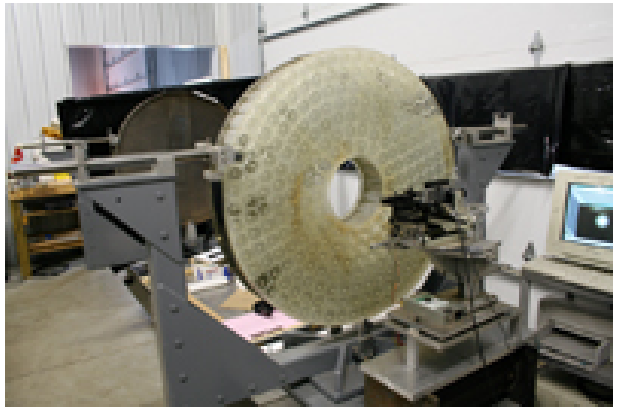
- From previous mirror designs the mass can be estimated using relationships which relate the mirror diameter (D in m) to the mirror mass (W in kg). For standard solid mirrors this relationship is typically: $W \propto D^3$

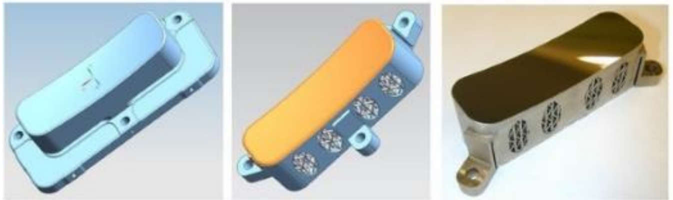
Light weighting Technique	Relationship	Diameter (m)	Predicted Mass (kg)
Classical light weighting	$W = 82D^{2.95}$	0.4	5.5
Sandwich mirror	$W = 68D^{2.9}$	0.4	4.76
Beryllium Mirror	$W = 26D^{2.31}$	0.4	3.13
Prototype sintered design	~	0.4	3



Relationships from: Valente, T.M. 1990. Scaling laws for light-weight optics, Proc. SPIE 1340, 47

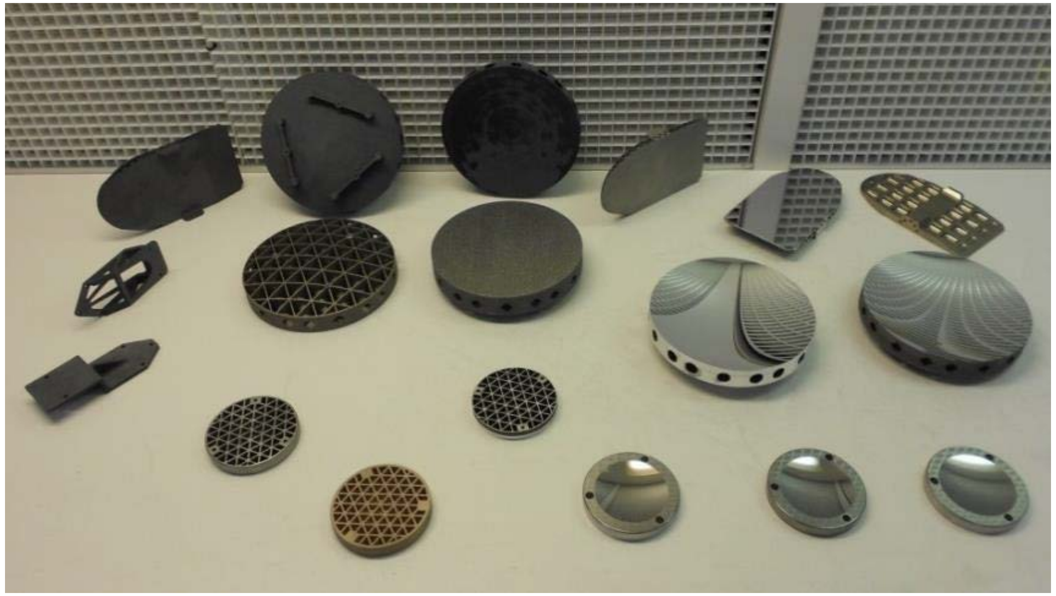
Light-weighting Mirrors (Competition)





Original design	New design	Selective laser melting
Mass: 284.6 g	Mass: 129.7 g	Mass: 127.7 g
Material: Al 6061		Material: Ti6Al4V
1st eigen freq ~2100 Hz		1st eigen freq ~2100 Hz
NiP coating		NiP coating

- TNO/ESA



- SPIE paper Martin Sweeney et all
- Proc. of SPIE Vol. 9574 957406-1

- The field is in flux, developments are fast and exciting

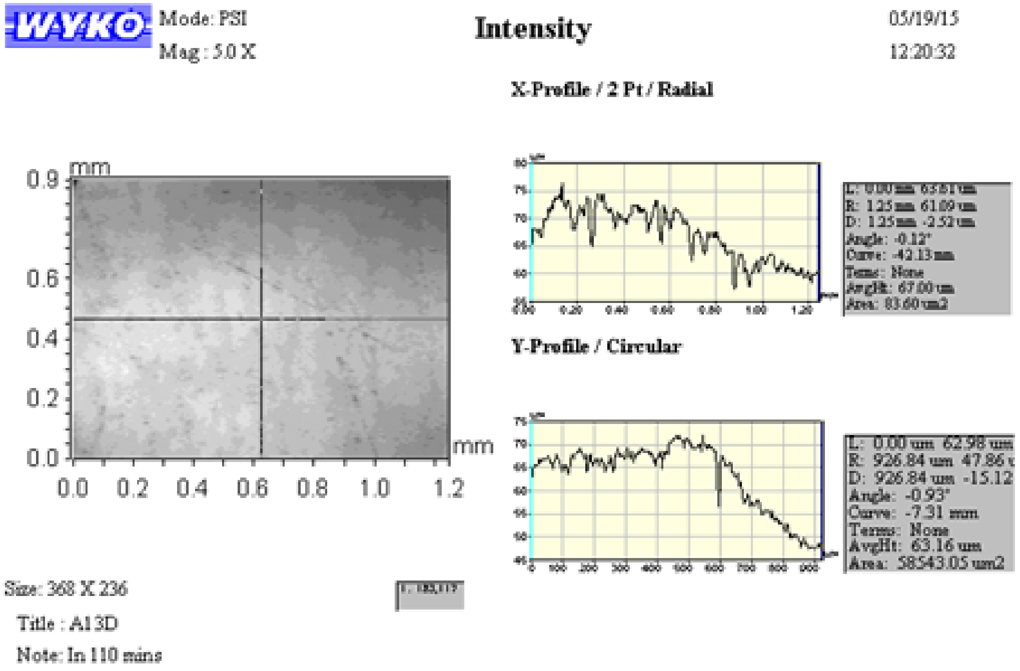
Advantages

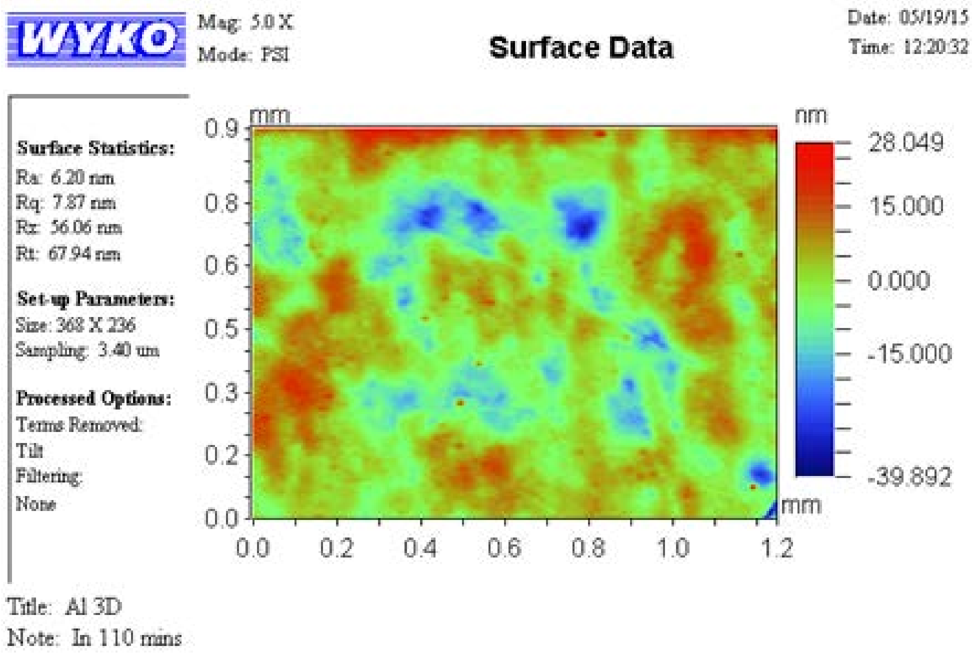
- Flexible in CAD design and free form optimisation
  - Structure design not limited by classical manufacturing technology
  - Cellular or lattice structures can be scaled to fit inside a semi enclosed volume
  - Densely distributed sub-structures to support mirror surface uniformly
    - Suppress quilting
  - Mass saving
  - Saving on material
    - One only uses the material to print, there is relatively little waste which is especially beneficial when the material used is expensive
  - Wide variety of materials available
    - Aluminium, Titanium, Steel, Copper, Beryllium, AlBeMet to name the main ones

Disadvantages – Stress and Scale

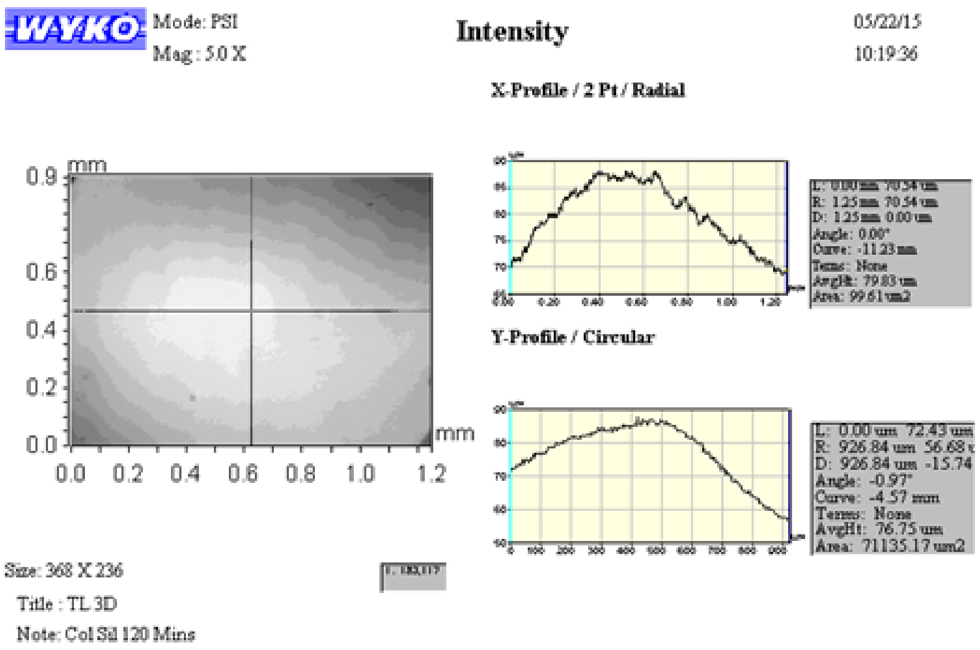
- DMLS
  - We are left with relatively high internal stress after printing
    - High internal (thermal) stress can destroy the build during printing
    - This is known and normally dealt with as part of the expertise of the supplier, but there can be surprises
  - Print size is currently limited
    - 250 mm x 250 mm readily available
    - 400 mm x 400 mm emerging fast now
- CAD
  - Current generation of CAD programs not geared up or optimised for 3D printing and the implementation of the internal cellular or lattice structures
  - Required memory often limits the detail in the scale of the structure being printed
  - 3D lithography files can be several gigabytes and take hours to transfer to the machine
- FEA
  - Some of the lattice structures are hard to model due to the scale of the model, general stiffness can be analysed obviously by condensing the detailed structure, but the finer detail important near edges will be lost

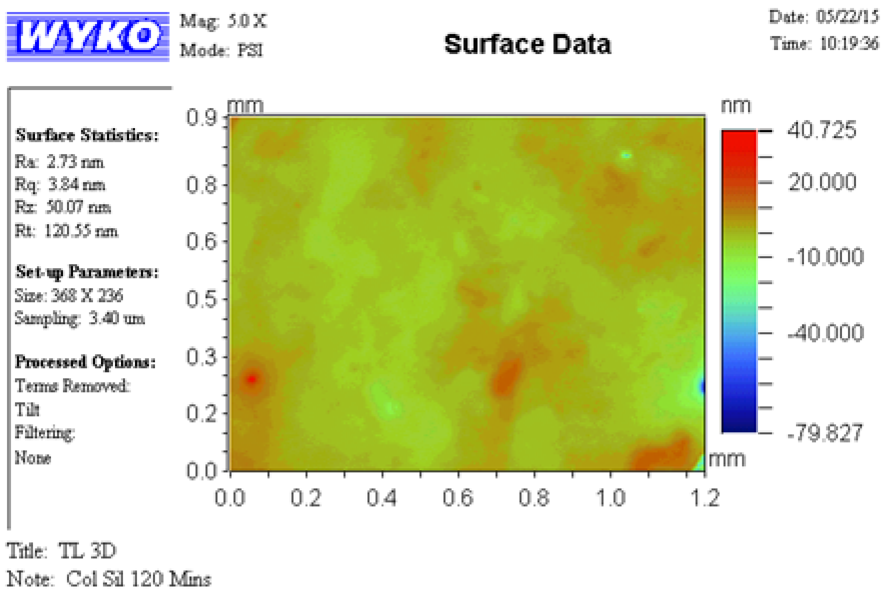
Aluminium AL 3D Polished Surface



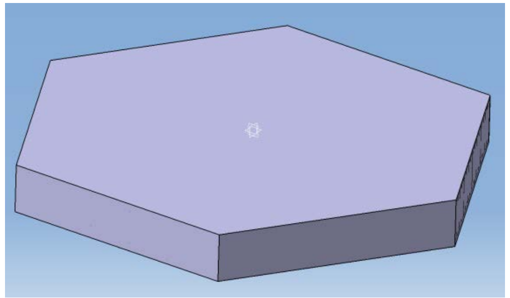


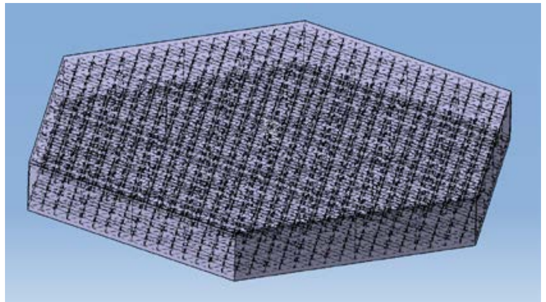
Titanium TL 3D Sample

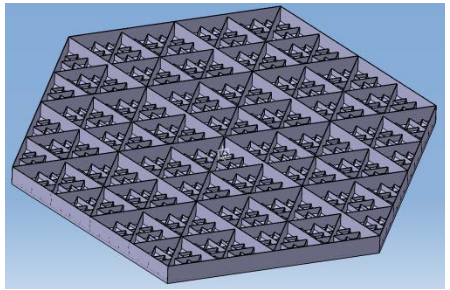




CAD Model (Early Concept)



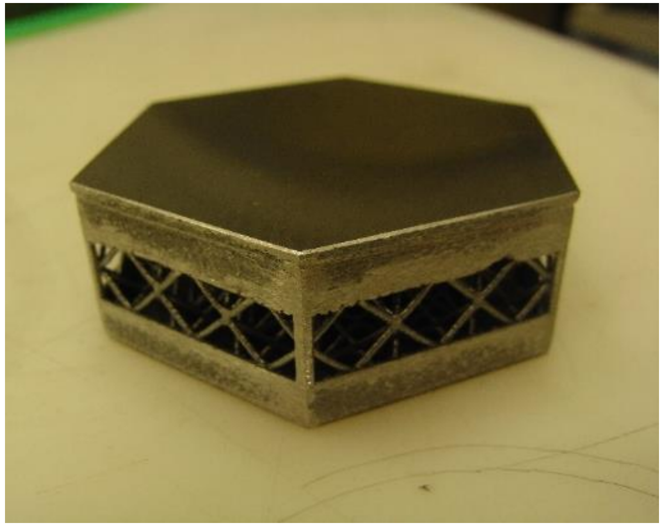


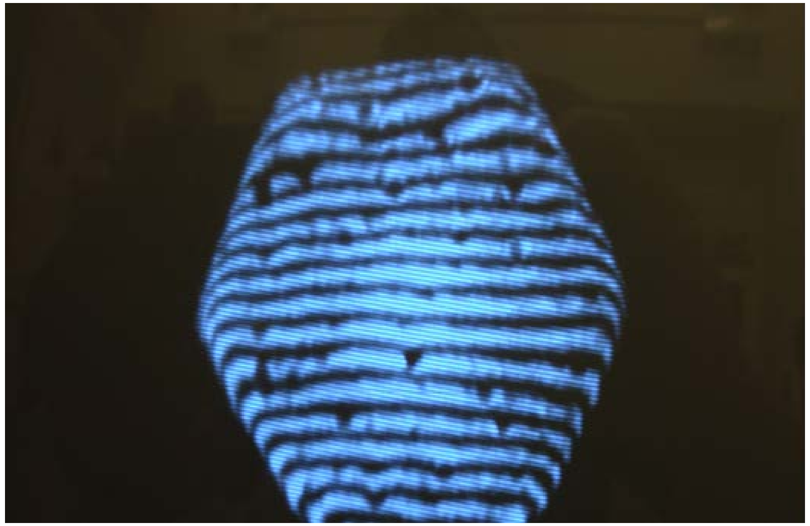


- Hexagonal shape
  - Internal stiffening
  - Symmetric
  - 240 mm diameter, 2mm skin for mirror surface
  - 510 gr
- It was decided early on to abandon the cellular design and go for a lattice
  - Limitations on the smaller details that can be printed favour lattice
  - Price to pay is lower torsional stiffness

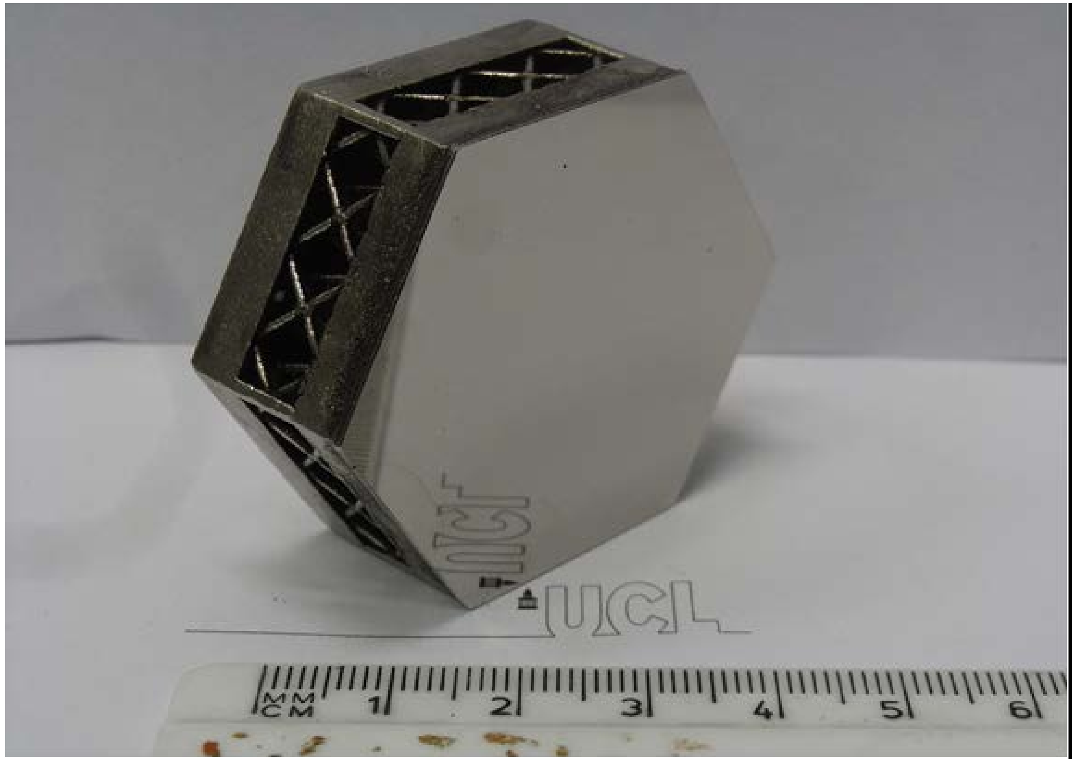
First Cut Test

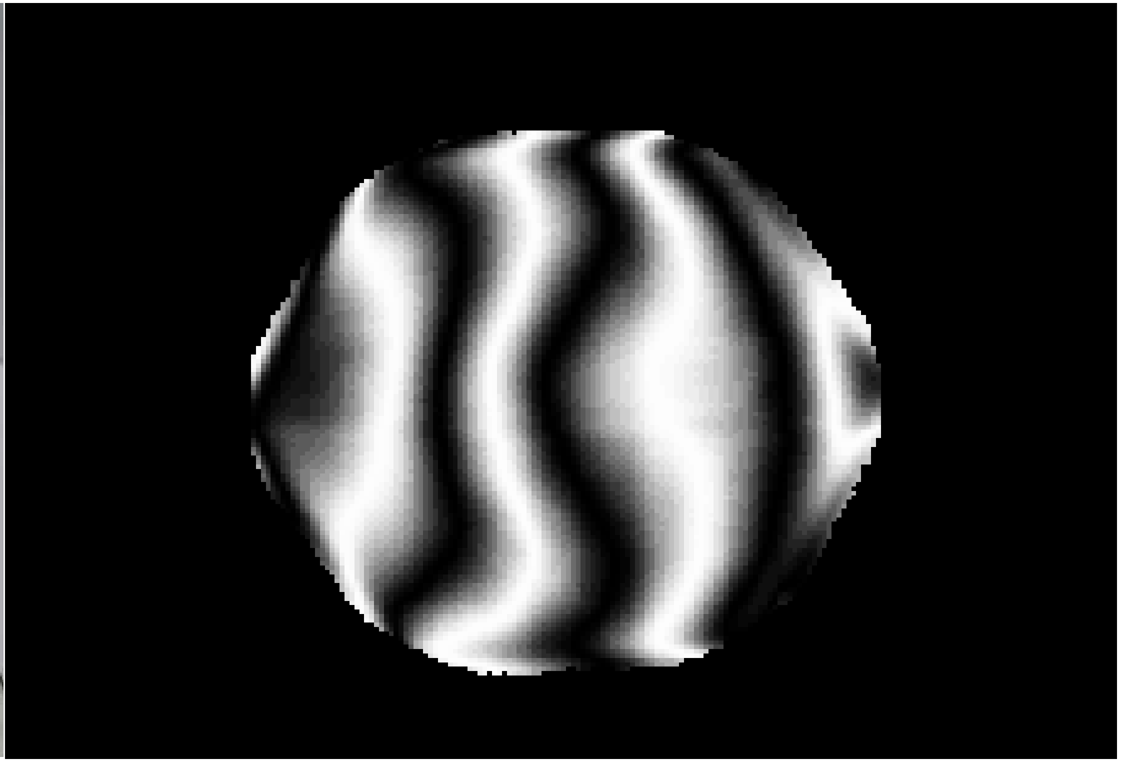
- To test the general principle we manufactured a small test mirror after processing material test samples first (Aluminium and Titanium
  - We selected Aluminium for the 3D printed test sample (60 mm)
  - Validate heat treatment



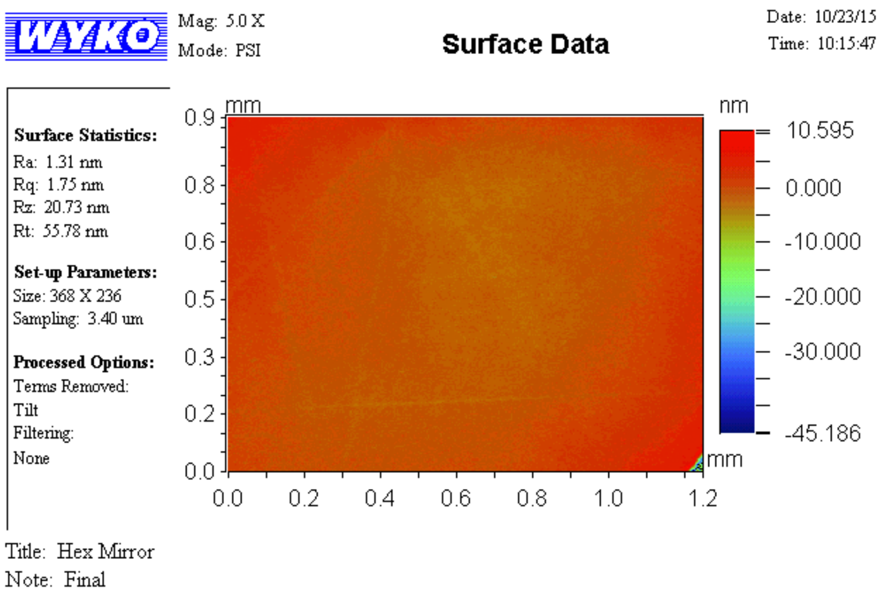


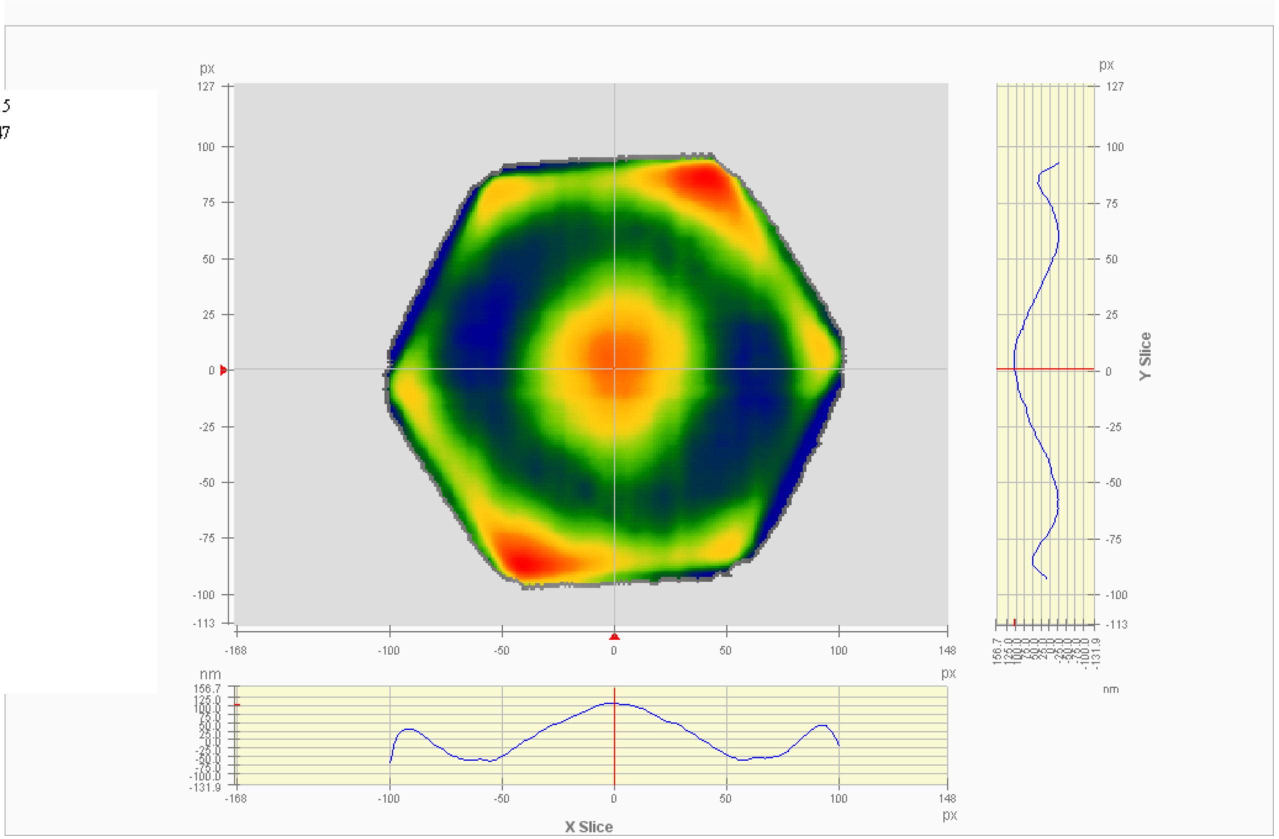
Nickle Coating and Polishing





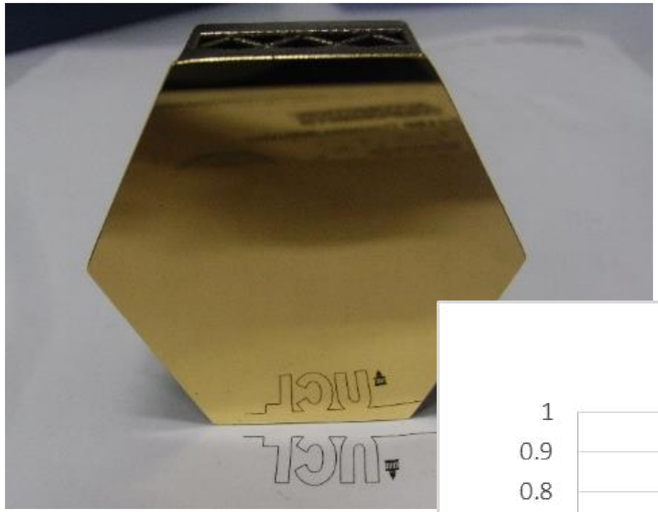
Surface Roughness and Final Figure



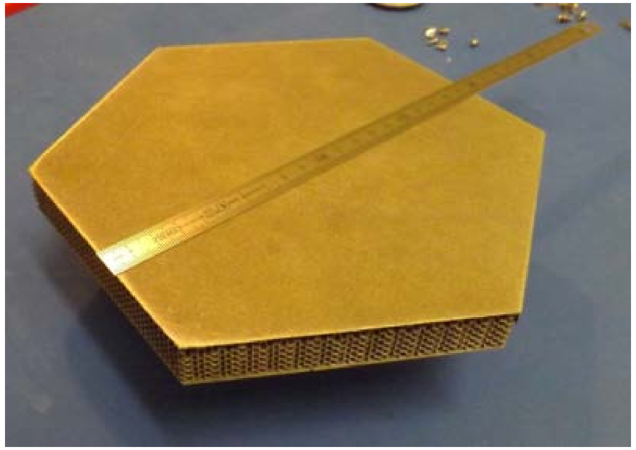


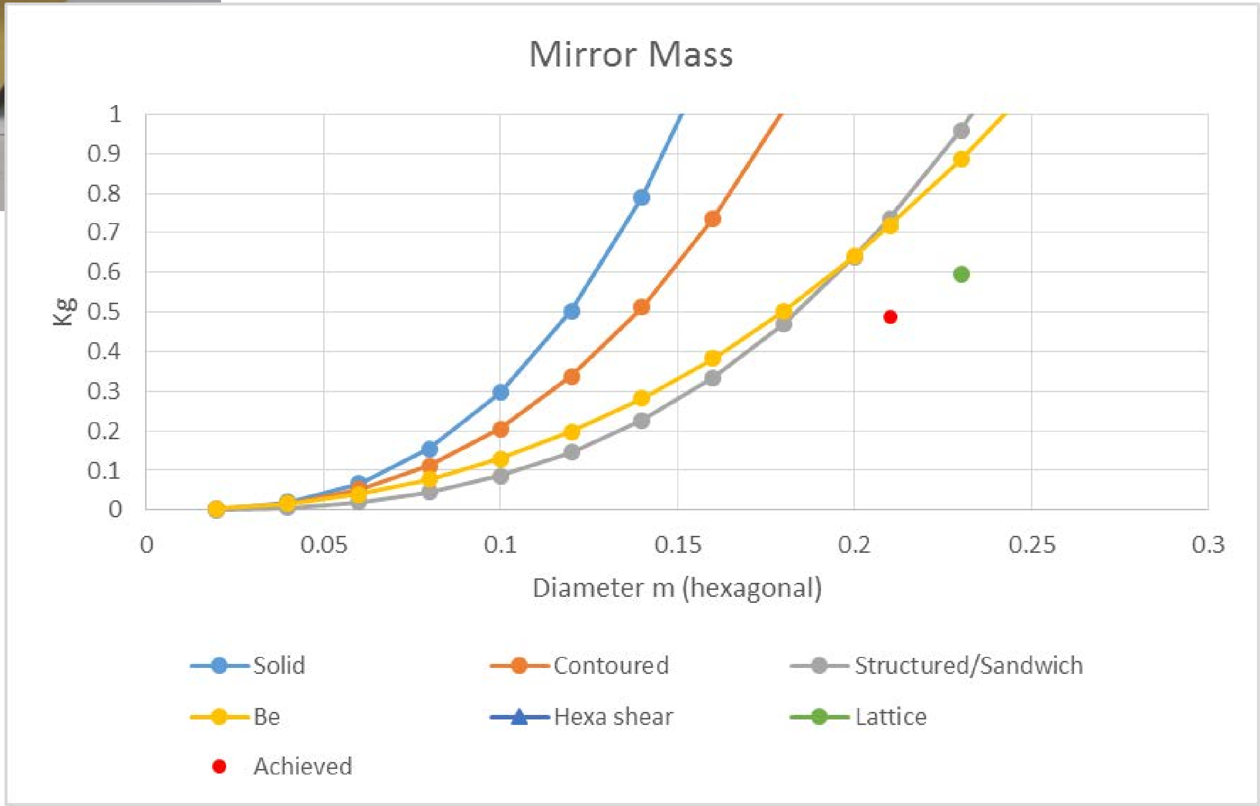
Currently underway

- Gold plated sample



- Larger mirror size



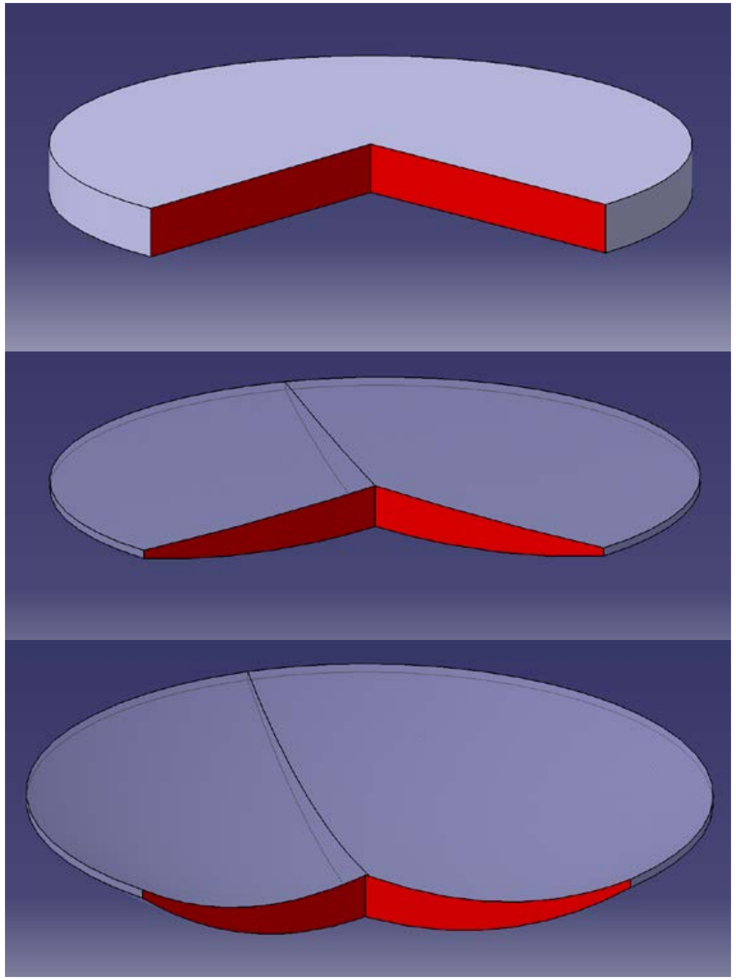


Demonstrator – Ground and First Polish

Findings

- It may not be possible to achieve a visible optical finish for the aluminium samples without coating, but that is expected. It should be possible to produce infrared and terahertz quality mirrors by this method however as was the objective
- The initial work on the titanium was concerning however once a suitable polishing technique was established. The quality of the surface is close to a visible light optical quality, no voids detected in the material
- Scale increase from 60 mm to 220 mm proved difficult due to software issues as well as manufacture problems. The problems were overcome but there are limitations to the model sizes that can be handled at present.
- We achieved close to 15 kg/m^2 for the first larger test sample with ample room for improvement (Aluminium)
- There are developments in manufacture up to 400 mm which is a very interesting size for a mirror (500-600?)
- Final demonstrator still being processed and waiting for surface roughness measurement

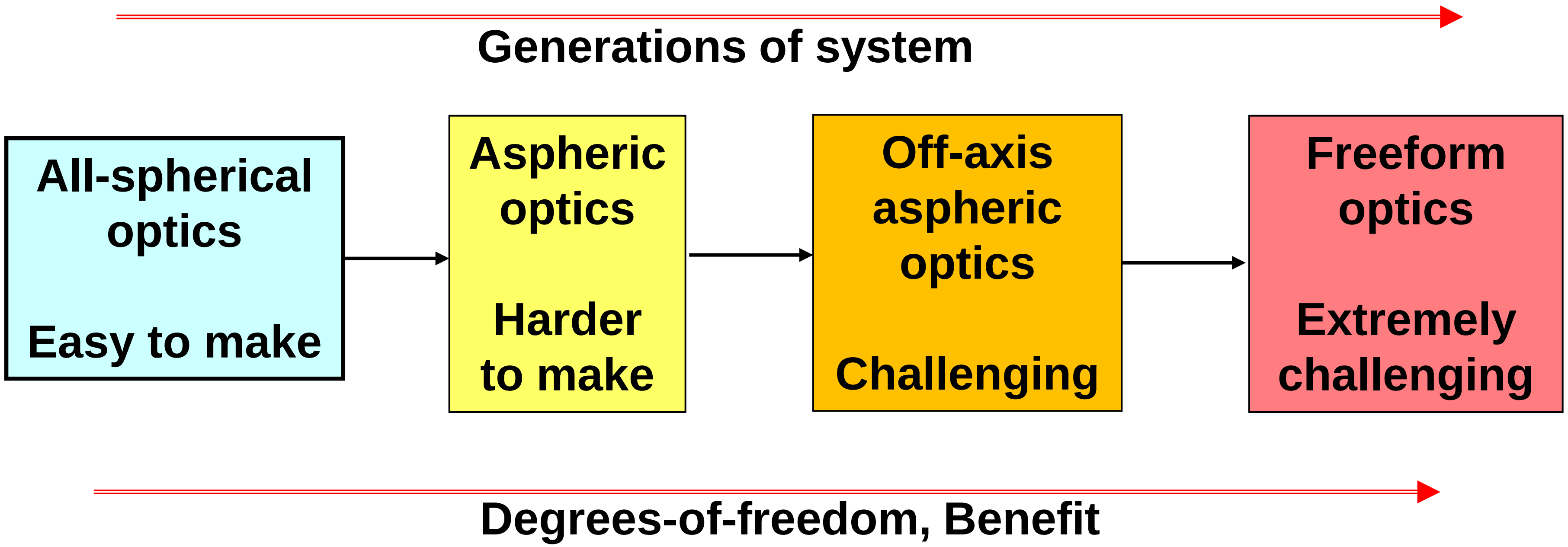
What Next?



- From a flat optical blank we need to go to:
  - Curved and maintain dimensional stability during and after printing
  - Verify lack of hysteresis (continued)
- And then….
  - The next big step in optics is free form
  - Extremely steep curves
  - Fast optics
  - It is a very interesting development that can save mass and volume, it favours smaller satellites

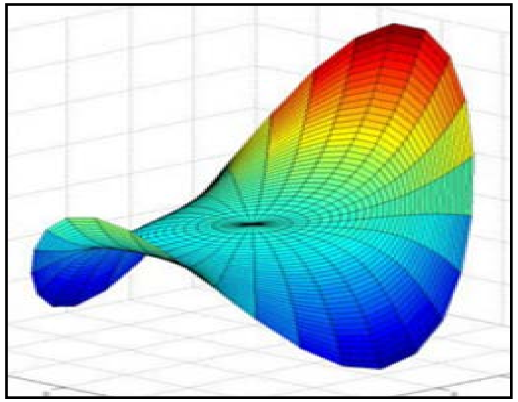
Requirements for Space Imaging Systems

- Optimising size + mass + performance demands:-
  - “fast” optical systems with steeply curved surfaces
  - more mathematical degrees of freedom in the design

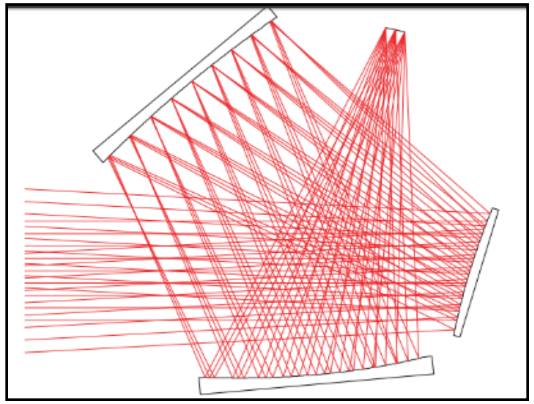


Freeform Optics

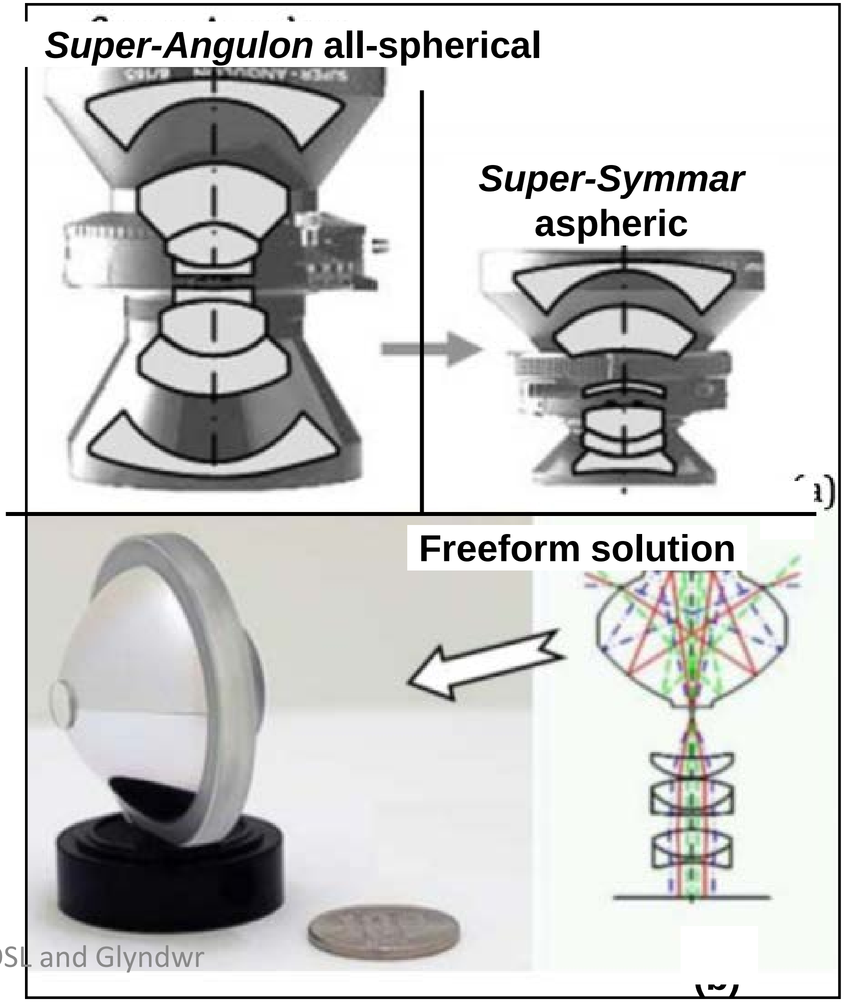
- *"A revolution, not an evolution"*
- Maximises degrees-of-freedom for the optical designer



Generalised freeform surface
No axis of symmetry

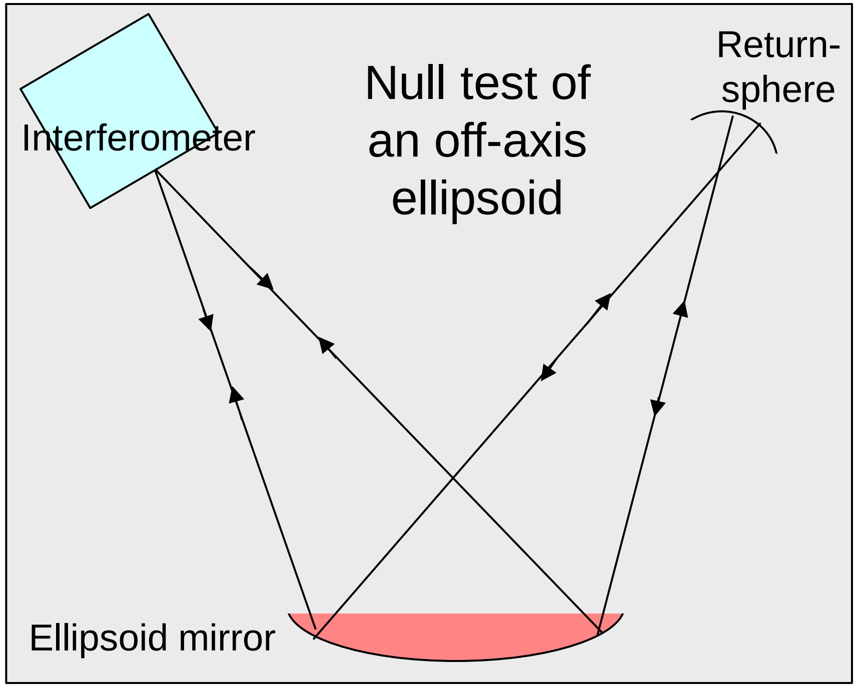


Compact freeform off-axis system



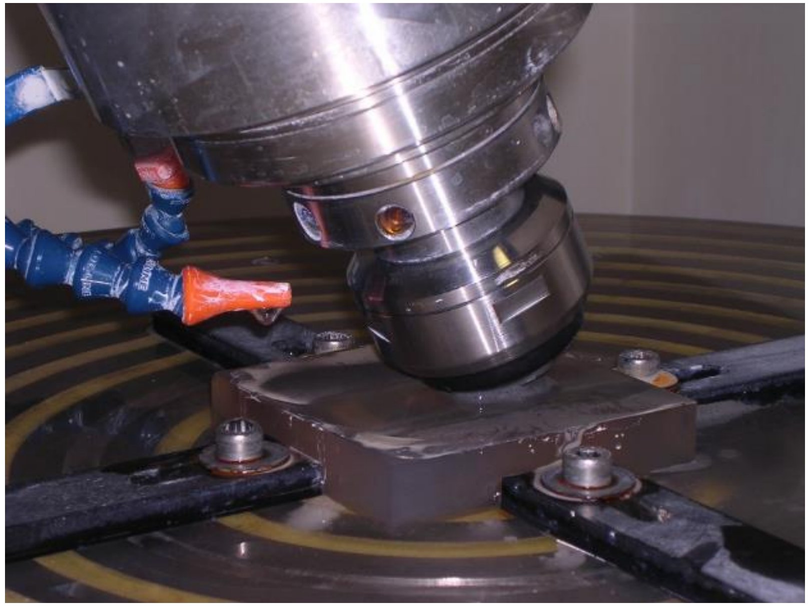
Additively-Manufactured Mirror Blanks. What Next?

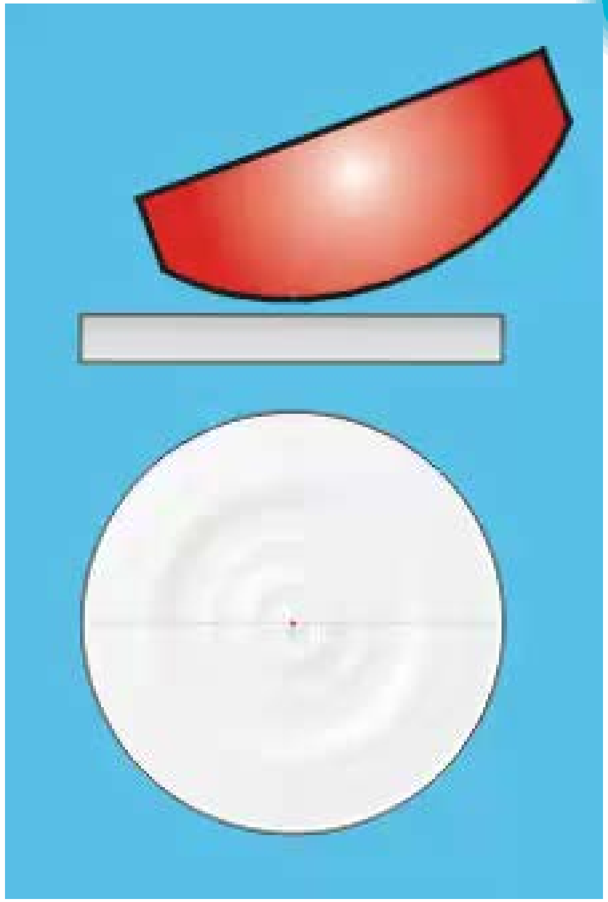
- Migrate from flat to a steeply-curved geometry
  - Free-form characteristics, but decoupling …
    … measuring the performance of the mirror, from the difficulty of measurement
  - Determine:-
    - Optimum geometry
    - Mechanical stability, hysteresis
    - Thermal stability, hysteresis
    - Porosity
    - Effectiveness of aspheric / freeform polishing methods



Polishing of Aspheres and Freeforms

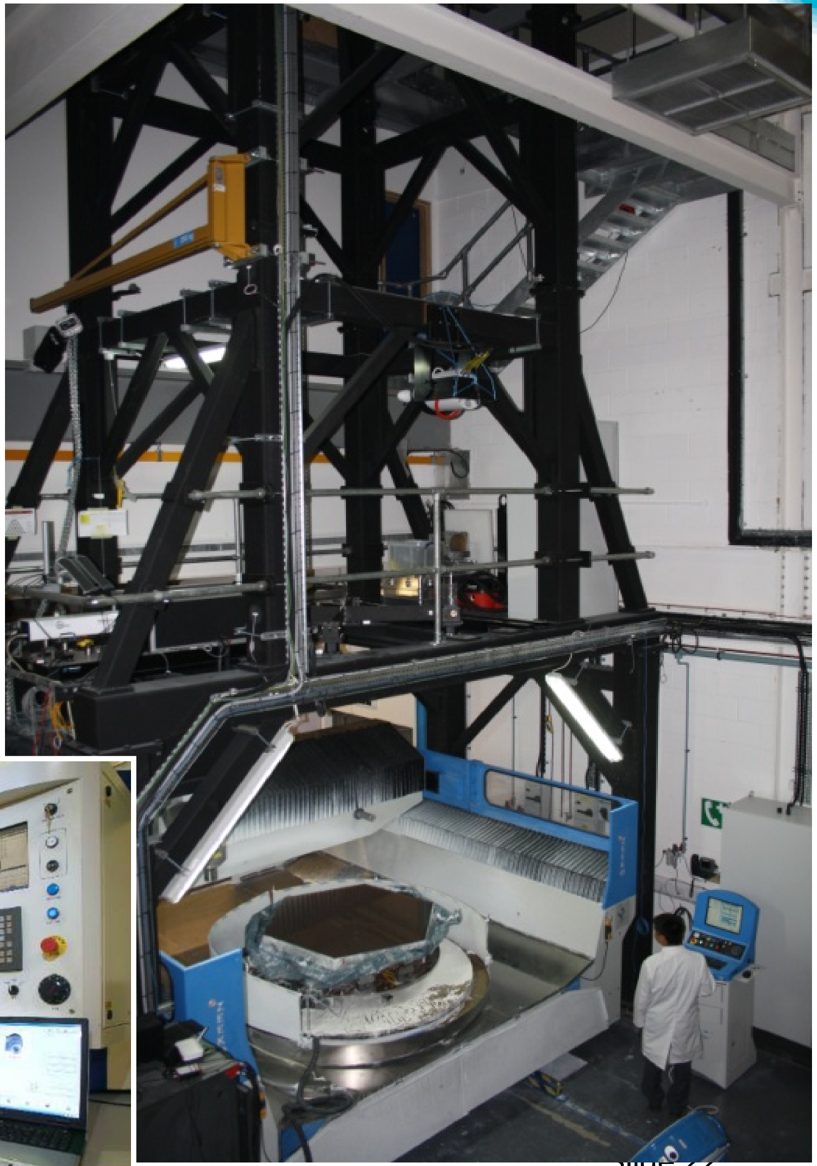
- Key issue is that a traditional tool can not fit the mirror-surface everywhere.
  - => mid spatial frequency errors ('ripples')
  - => stray light and image degradation





Inflated or elastomer bonnet adapts to local surface topography, and gives polishing spot of variable size

National Facility for Ultra Precision Surfaces, St Asaph, North Wales



Continue With….

- Investigate developments in CAD with regard to lattice works
- Print a steeply curved mirror blank
  - Grind and polish
  - Show that free form surfaces are within reach for this technology without fear of hysteresis
  - Metrology
- Stiffness verification
  - Verify mathematical tools
- NDI
  - Non destructive inspection of build quality
    - Internal crack detection (Ultra Sound, X-ray at all applicable?)
    - Vibration testing and check damping?

Questions