

Lightweight mirrors for X-ray astronomy leveraging 3D printing of fused silica: first results

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ABSTRACT

A successor to the *Chandra X-ray Observatory* needs to combine high precision mirrors to achieve sub-arc-second spatial resolution with thin stiff mirror substrates to provide a large collective area; to date this combination remains elusive for a complete mirror shell. We present results from an ESA OSIP Study that offers a new approach to X-ray mirror fabrication by leveraging 3D printing in fused silica to print stiff lightweight full shells which are subsequently polished to achieve optical performance. The primary objective of the study was to design, 3D print, and polish a cylindrical lightweight segment to demonstrate the integration of lattice structures to reduce mass, and a route for mirror manufacture towards X-ray reflection. Complementing this objective, we investigated how print orientation affects surface roughness by printing flat square samples (36 mm length, 5 mm thickness) and subjecting the samples to lapping, polishing and pitch-polishing, and how the 3D printed fused silica material behaves in a vacuum and its associated outgassing rate.

Three cylindrical prototype segments (244.5 mm radius of curvature by 100 mm×100 mm) in three designs were 3D printed using vat photopolymerisation. The prototypes included a solid design (5.0 mm thick) alongside two latticed designs (8.5 mm thick): a surface-based periodic lattice, and a 2.5D extruded cellular biomimetic lattice. We optimised the lattices to minimise distortions along the cylinder length. Metrology of the as-received prototypes highlighted a $\sim 1\text{ }\mu\text{m}$ root mean square (RMS) surface roughness and hundreds of microns of deviation from the intended shape. Polishing commenced on a biomimetic design with a visual reduction in surface roughness noted. In parallel, we demonstrated that print orientation does not affect surface roughness with a sub- μm RMS roughness demonstrated on two orientations after pitch-polishing; and we have commenced outgassing measurements by recording a pressure difference via the Throughput Method. Our first results signal a clear opportunity for 3D printing in fused silica to deliver lightweight mirrors for high spatial resolution X-ray astronomy, and further, broader applications for normal incidence mirrors at infrared to ultra-violet wavelengths.

Keywords: X-ray telescopes, 3D printing, fused silica, lightweight mirrors, lattices, polishing

1. INTRODUCTION

We present the results from an ESA Open Science and Innovation Platform (OSIP) Study that asked the question, can you 3D print mirrors for X-ray astronomy? X-ray telescopes delivering high spatial resolution for imaging currently rely upon thick, heavy, monolithic mirror-shells that are figured, polished and aligned to a very high precision. However, the mass and thickness limit the collecting area of the telescope, and despite decades of technology development, a lightweight, high spatial resolution mirror-shell remains elusive.¹ Can 3D printing provide a solution? Lightweight structures, such as lattices and biomimetic geometries, are a key benefit of 3D printing (additive manufacturing) and software packages are available for optimising structures. Likewise, 3D printing in fused silica is commercially available, thereby providing a material with beneficial thermal and mechanical properties for X-ray mirror fabrication. Our OSIP study explored both the suitability of lightweight

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geometries, and the behaviour of 3D printed fused silica for X-ray astronomy by printing and optically polishing simplified cylindrical segments from a mirror-shell.

The *Chandra X-ray Observatory* (CXO; launched 1999)² is the current X-ray observatory operating for high resolution imagery. CXO leverages four large diameter (630 mm to 1200 mm), thick (16 mm to 24 mm), full shell, mirror pairs to accurately reflect the X-rays onto the detector.³ The tubular shells in the Wolter I configuration were fabricated in Zerodur to limit thermal distortions. The most recent proposed successor to CXO was *Lynx*;⁴ submitted into the US “Decadal Survey on Astronomy and Astrophysics 2020”, *Lynx* would be transformational for X-ray astronomy by providing a 3000 mm diameter outer mirror and an effective area of $\sim 20\,000\text{ cm}^2$ at 1 keV⁴ (in comparison, CXO’s effective area is 770 cm^2 at 1 keV⁵). The challenge for *Lynx* was to retain the angular resolution of CXO and whilst using significantly thinner shells to increase the effective area. *Lynx* evaluated two optical approaches: full shells in metals⁶ or fused silica;^{7,8} and segmented shells, either static high precision monocrystalline silicon substrates,^{9,10} or adjustable glass substrates to correct for manufacturing errors.¹¹ Although *Lynx* was not prioritised, the published report¹² recommended continued technology maturation. Our study aligns with this goal and adds to the full shell optical approach by 3D printing lightweight mirror full shells to reduce time, cost and waste, whilst implementing direct polishing heritage gained from previous X-ray imaging telescopes.

3D printing offers an optical engineer with a fourth approach to lightweight mirror fabrication. For conventional lightweight mirrors for normal incidence, infrared to ultra-violet (UV), the engineer may either remove the material via machining; limit the material with inverse moulds by casting; or limit the material by constructing a low mass structure from individual parts. In contrast, 3D printing builds an intricate lightweight structure layer-by-layer, thereby limiting material use. The four approaches, machining, casting, constructing, and 3D printing, offer different lightweight mirror attributes, and an engineer will trade off ease of manufacture (cost & time), lightweighting percentage, and mirror stiffness depending on requirements. At grazing incidence (X-ray), there is a high sensitivity to mid- to low-spatial frequency distortions (surface form error) along the length of the tubular mirror (axial direction). Therefore, when incorporating a lightweight structure, a uniform support along the axial direction is necessary. Structures are available that meet this requirement, such as extruded lattices (2.5D lattices), or tripy periodic minimal surface (TPMS) lattices (surface-based lattices). In particular, extruded lattices can be designed to be biomimetic, and considering the tubular X-ray mirror geometry there are clear parallels with plant stems. For example, the cellular structure of a plant stem can be recreated digitally using Voronoi cells and this is a common functionality of 3D printing design software.

3D printing lightweight mirrors for X-ray telescopes was first presented in 2017,^{13,14} but a major constraint at the time was the material availability, limiting the study to aluminium and polymers. Following a decade of research and development, 3D printing in fused silica offers a new opportunity: a commercially available material with X-ray telescope heritage.¹⁵ Today, there are at least six printer technologies that offer fused silica,^{16–25} but when considering our requirements (large print volume, commercial ability & print resolution), vat photopolymerisation (VPP) currently offers the optimum technology to recreate intricate lattices and biomimetic structures. VPP fused silica divides into two categories, stereolithography (SLA) which uses a UV laser and a scanning mirror to photopolymerise a track of resin layer-by-layer,²¹ and digital light processing (DLP) which projects a UV source in the required cross-section to photopolymerise a complete layer simultaneously.²³ Three recent studies have explored VPP fused silica for future normal incidence lightweight mirror applications.^{26–29} The most recent study, Bissell, L. *et al.* 2026, *sub.*,²⁹ polished three silica materials (fused silica, fused quartz, and DLP fused silica) and demonstrated comparable sub-nm surface roughness across the materials. These first studies are encouraging; however, for X-ray applications we require $<0.5\text{ nm}$ root mean square (RMS; Sq) surface roughness, geometries suitable for X-ray reflections, and a greater understanding of the VPP material behaviour.

Our OSIP study explores the potential of VPP fused silica to create full mirror shells for a future high resolution, large collecting area X-ray telescope. At the core of the study is the design, 3D printing, and optical fabrication of prototypes intended for X-ray reflection. The prototypes are simplified cylindrical segments of a full shell and explore three designs: a solid, a TPMS lattice, and a biomimetic cellular lattice. We print the three designs at a commercial DLP supplier; assess the prototypes for in-coming surface form error; and select the optimum prototype for lapping and polishing. Complementing the core study are two satellite studies, the first investigates how the print-orientation affects the surface roughness after lapping, polishing, and pitch

polishing, and the second quantifies the outgassing rate of DLP fused silica. Herein, we present an overview of our OSIP study and reference the results from two published conference proceedings: *Civitani, M. M. et al 2026*³⁰ describing the influence of print-orientation on surface roughness after pitch polishing, and *Westsik, M. et al 2026*³¹ detailing the design requirements and lattice optimisation resulting in the three cylindrical prototypes. Our overview also includes the initial lapping and polishing of the selected prototype and the experimental procedure for the outgassing measurements.

2. 3D PRINTED FUSED SILICA

Our OSIP study used a single supplier of DLP fused silica (Glassomer GmbH, Germany) and received all parts as-sintered; therefore, the supplier undertook printing and thermal post-processing: debinding at 600 °C to remove the polymer and then sintering at 1300 °C²⁶ to form the fused silica. Purchasing from a commercial supplier for our 3D printed fused silica is analogous to conventional optics manufacturing where mirror blanks are bought directly from glass manufacturers for processing. The team iterated with the supplier to define design rules to ensure successful prints without the need for sacrificial support structures, which could result in surface defects at the point of contact. Therefore, when designs were complete, we sent the `.stl` or `.step` files alongside a mechanical drawing to the supplier and allowed the supplier to follow their in-house best practice. A mechanical drawing was supplied to ensure that a print orientation was documented for each part and that the correct dimensions were represented when the files were loaded within the 3D printing slicer software. All parts were printed on a Asiga Pro DLP printer (Asiga, Australia) using the Glassomer SL-V2 photopolymer resin. The printer used a layer height of 50 µm, a spatial resolution of 80 µm, and a print volume of 164 mm×90 mm×150 mm (x, y, z).

2.1 Flat samples: evaluation of print orientation and pitch polishing

This study investigated the difference in surface roughness between horizontal and vertical printing orientations after lapping, polishing and pitch-polishing. Previous investigations^{26,27,29} only reported on a horizontal orientation, where the polished surface was generated within the printed layer; however, to eliminate support structures the cylindrical prototypes require a vertical print orientation, where the polished surface intersects potentially thousands of 50 µm layers. Further, the previous investigations did not attempt pitch-polishing, which is considered a necessary final step to achieve ‘super polished’ surfaces (<0.5 nm Sq). Therefore, we designed 36 mm square samples with a 5 mm thickness (flat) and printed three samples in both orientations as shown in Figure 1, and performed iterations of lapping, polishing and pitch-polishing, alongside optical metrology, to quantify Sq surface roughness.

We provide a thorough description of this study in *Civitani, M. M. et al 2026*³⁰ and as such provide only a summary of the conclusion here. The in-coming metrology demonstrated, as expected, that the vertical samples exhibit a higher average surface roughness with a larger standard deviation than the horizontal samples, with the 50 µm layers clearly visible under microscope on the vertical samples. After five lapping and polishing runs, the final surface roughness converged to <1 nm Sq for all samples, with no statistical difference between horizontal and vertical orientations. Pitch polishing (Run 6) reduced the surface roughness to $\lesssim 0.3$ nm Sq, with no statistical difference between orientations. These results confirm that the intersected layers in the vertical orientation do not degrade the surface roughness and supports a vertical orientation as a viable route for the cylindrical prototypes and, eventually, full-shell X-ray mirrors.

2.2 Cylindrical prototypes

2.2.1 Design

The paper by *Westsik, M., et al. 2026*³¹ describes the three cylindrical prototypes designed and printed for the OSIP project; Table 1 presents a summary of the final specifications for each design and the `.stl` files can be downloaded via open data.³² The solid and lightweight lattices have different total thicknesses (5 mm and 8.5 mm respectively) due to a maximum thickness limitation of 5 mm to ensure complete debinding. Both lattice designs used a lattice wall thickness and a blend radius of 1 mm, these parameters define the thickness of the lattice and the fillet radius used to blend the lattice into the interconnecting solid structures. The TPMS prototype used a TPMS Diamond lattice with a cylindrical cell map (arrangement of lattice unit cells) in a 10 × 10 × 1 unit cell

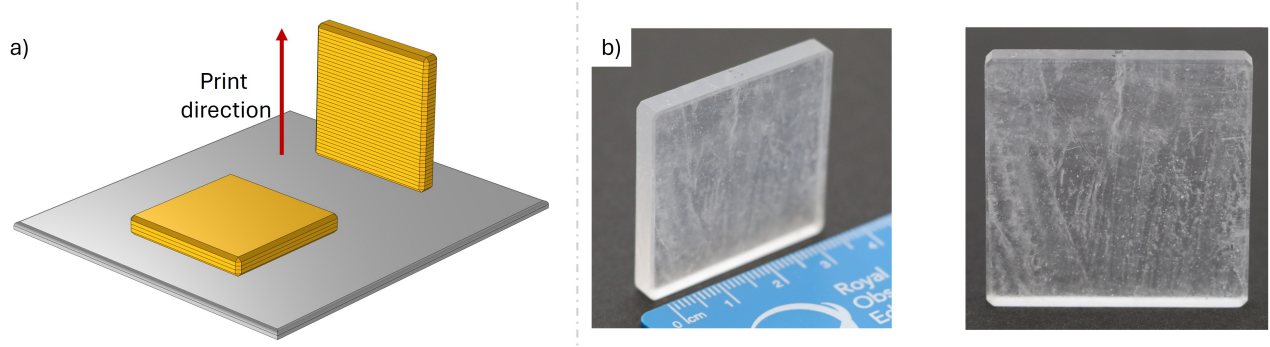


Figure 1: (a) the two print orientations of the square samples; and (b) a horizontal sample as received from the supplier highlighting the starting surface texture. Image credit (b): J. Cowan, STFC.

Universal specifications

Parameter	Value
Geometry	Cylindrical
Inner ROC	244.5 mm
Dimensions	100 mm $\times$ 100 mm
Thick. solid	5 mm
Thick. lightweight	8.5 mm
Chamfers	1 mm on external edges

Lightweight universal specifications

Parameter	Value
Lattice thick.	5 mm
Top face thick.	2 mm
Back face thick.	1.5 mm
Lattice wall thick.	1 mm
Blend radius	1 mm
Min. channel diameter	1.5 mm

TPMS Lattice

Parameter	Value
TPMS lattice	Diamond
Cell map (geo.)	Cylindrical
Cell map (size)	10 $\times$ 10 $\times$ 1
Side wall	Open
LMR	69%
OMR	41%

Voronoi Lattice

Parameter	Value
# seed pts	65
Min. pt spacing	7 mm
Max. pt spacing	16 mm
Side wall	Closed
LMR	49%
OMR	29%

Table 1: The specifications of the three cylindrical prototypes

arrangement (*azimuthal* $\times$ *axial* $\times$ *radial*). The Voronoi lattice prototype used 65 seed points to generate the Voronoi cells, where the seed points were randomly positioned within minimum and maximum seed spacings. The 2D Voronoi cells generated the 2.5D lattice by extrusion, resulting in a tubular cell-like structure. The LMR and OMR parameters refer to the lightweighting percentages: LMR (lattice mass reduction) describes only the lattice and is defined as the mass removed due to the lattice in comparison to a solid equivalent geometry; whereas the OMR (overall mass reduction) describes the prototype (lattice + face plates + side walls) and is defined as the mass removed from the prototype due to the lattice in comparison to a solid equivalent prototype. Therefore, a higher OMR percentage denotes more mass reduction and lighter prototype.

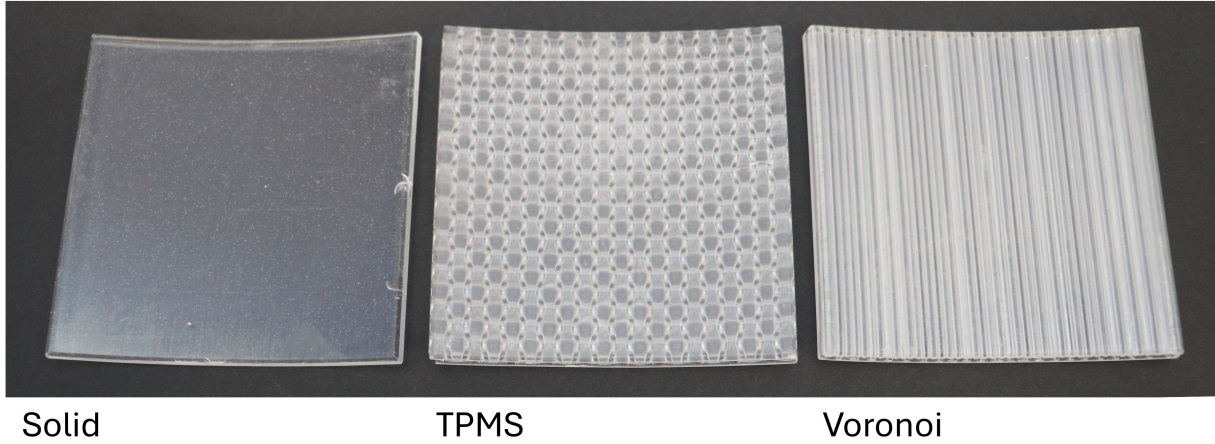


Figure 2: The three cylindrical prototypes designs, Solid, TPMS and Voronoi (*left to right*); dimensions - 100 mm×100 mm×5 mm (solid) or ×8.5 mm (lightweight), 244.5 mm inner ROC; photographed examples represent those selected for outgassing tests, not polishing. Image credit: J. Cowan, STFC.

2.2.2 3D printing and in-coming metrology

Figure 2 presents examples of the three designs after printing, debinding and sintering; three prototypes were printed in each design to ensure redundancy. The supplier printed each prototype individually on the build plate, rather than printing multiple prototypes simultaneously. A visual inspection of the prototypes highlighted some printing defects: cosmetic and structural. Cosmetic defects refer to marks on the prototypes due to the printing and thermal processes and influence the surface texture. Whereas structural defects refer to short (1 mm to 2 mm) cracks in the printed fused silica. The cosmetic defects were ubiquitous across all prototypes, in contrast structural defects were present only in a subset of prototypes.

*Civitani, M. M., et al 2026*³⁰ describes the in-coming metrology of the nine prototypes*: surface roughness and surface form error. A contact profilometer SurfTest SJ-210 (Mitutoyo, Japan) evaluated the roughness in the axial and azimuthal directions via a line scan. The measured RMS roughness (R_q) exhibited a higher roughness in the axial than the azimuthal direction; expected given the stylus traversed multiple build layers axially but remained in-plane within a single layer azimuthally. Averaging the axial and azimuthal R_q values for each design gave the starting surface roughness: Solid = $(1.10 \pm 0.52) \mu\text{m}$, TPMS = $(1.22 \pm 0.54) \mu\text{m}$, and Voronoi = $(0.90 \pm 0.37) \mu\text{m}$.

The surface form error of the nine prototypes all diverged from the intended cylindrical optical prescription. The measured radius of curvature (ROC) on the solid prototypes was larger (254 mm to 257 mm) than the 244.5 mm baseline, attributed to dimensional changes during the printing and/or thermal processes. A bespoke contact profiler (Characterization Universal Profiler, CUP³³) measured the ROC of the solid prototypes; however, the profiler failed to register accurate positions on the latticed prototypes due to varying transparency. A second non-contact profiler, CHR 3300 chromatic confocal sensor (Precitec, Germany), measured the prototypes in axial strips at seven azimuthal locations; however, ROC information could not be retrieved via this method. The CHR 3300 data was processed to remove outliers and tip/tilt associated with alignment. The RMS surface form error ranged from 41 μm to 84 μm (solid), 31 μm to 74 μm (TPMS), and 84 μm to 96 μm (Voronoi). From the three designs, the Voronoi prototypes proved the most repeatable in surface form error by each exhibiting a parabolic form in the axial direction and as such, we selected VR01 for optical polishing.

2.2.3 VR01 Polishing - preliminary results

We bonded the VR01 prototype upon an aluminium fixture using a temporary thermoplastic adhesive (Unibond 5.0 adhesive; Universal Photonics, USA), to ensure the necessary stiffness under polishing. The thickness of the

*Labelled: SM01→SM03 (Solid), TPMS01→TPMS03 (TPMS lattice), and VR01→VR03 (Voronoi lattice)

adhesive was not uniform as it filled the ROC mismatch between VR01 and the fixture. Mounted in this way, the prototype + fixture could be readily interfaced with either the polishing machine or the different metrology systems, as shown in Figure 3. The CHR 3300 profiles of the VR01 after bonding, and used as the input geometry for polishing, demonstrated a form error from the nominal cylindrical shape of $77.8\text{ }\mu\text{m}$ RMS and $382.2\text{ }\mu\text{m}$ PV (peak-to-valley).

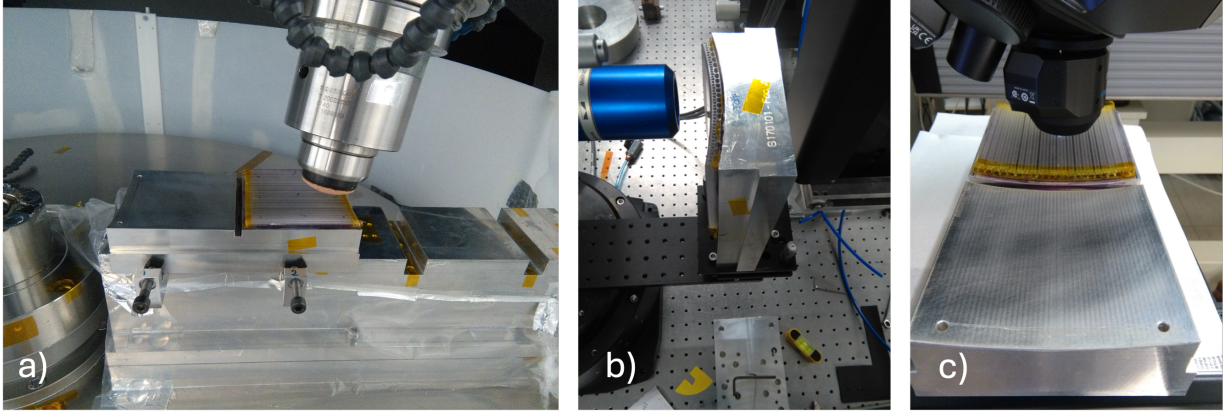


Figure 3: a) VR01 interfaced to the optical table of the IRP1200 Zeeko machine; b) VR01 on RotScan measurement setup, the CHR sensor being visible on the left; c) VR01 under optical microscope VHX-X1 series by Keyence

Due to the cylindrical form, our approach to polishing differed from the square samples reported in Section 2.1 which used a lapping and polishing machine with interchangeable flat lapping/polishing plates. For VR01 we applied bonnet polishing via a Zeeko IRP1200 machine (Zeeko, UK), thereby bypassing the lapping phase and progressing immediately to polishing. The impact of this approach is a reduction of rapid material removal (removal rate) to reduce the RMS and PV of the surface texture, requiring an overall increase in processing time to achieve equivalent results. The IRP1200 rastered a $\sim 40\text{ mm}$ ROC pressurized (1.1 bar) bonnet across an area of $70\text{ mm} \times 60\text{ mm}$ centered on the sample concave surface. The bonnet tool was covered in a LP-66 cerium oxide filled polyurethane pad and pressed against the surface by a nominal offset of 0.25 mm , providing a contact spot of $\sim 10\text{ mm}$. The precessed tool at 15° from the normal was spinning at 700 rpm and moving with 200 mm min^{-1} transverse speed. Spacing between adjacent rastering lines of 0.4 mm was chosen. A recirculating abrasive fluid made of cerium oxide (Super CEROX 1663) mixed with water was set to have a density of about 1.006 g cm^{-3} . The run duration was $\sim 56\text{ min}$.

Due to the large deviation (hundreds of microns) from the 244.5 mm cylindrical form, the as-measured shape of the concave surface was considered as the input geometry to define the polishing process (Figure 4). The first polishing run aimed to verify the polishing behaviour while assessing both the integrity of the prototype and the removal rate of material. Therefore, we targeted a uniform material removal across the surface without intentional figure correction. We estimated a removed thickness of $\sim 7\text{ }\mu\text{m}$ to $8\text{ }\mu\text{m}$, based on previous polishing datasets and assuming fused quartz as a reference material. The polished area was defined at the centre of the full surface, 70 mm wide in the axial direction and 60 mm in the azimuthal direction, leaving the unpolished contour as a fiducial for estimating the material removed. An optical microscope with $100\times$ magnification imaged VR01 at different positions after polishing, showing a clear reduction of the surface texture. Figure 5 displays this reduction by imaging at the transition between the unpolished and polished surface.

To quantify the azimuthal pattern caused by the extruded tubes, height data from the surface were acquired via continuous motion about the rotational axis. We sampled the azimuthal profiles with an interval of $\sim 20\text{ }\mu\text{m}$ at three positions (Figure 6): at the top of the sample (Profile 01; unpolished region), at the centre of the polished area (Profile 04), and at the bottom (Profile 07; unpolished region). The azimuthal profiles were extracted from the height data by removing leading/trailing zero-padding; trimming the noisy data at the surface-air interface; rejecting residual outliers via a moving-median filter; and finally, characterising the shape and local noise by first- and second-order polynomial detrending and a moving-window standard deviation of the shape-subtracted

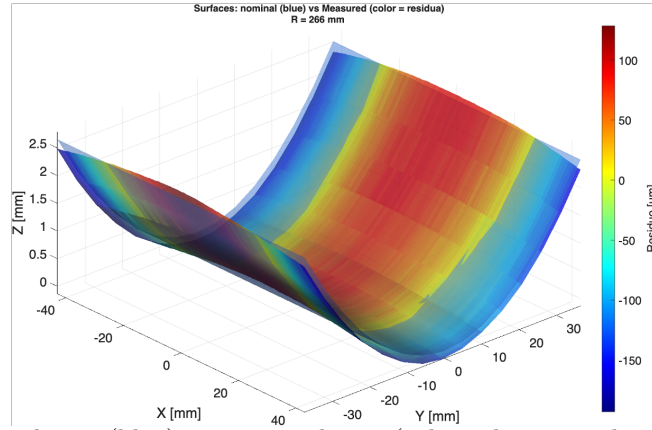


Figure 4: Nominal geometrical map (blue) vs measured map (coloured map, with colours indicating the residual error with respect to the nominal geometry) of the cylindrical surface, used to input the polishing process of VR01. X (mm) is the axial direction, Y (mm) is the azimuthal direction, Z (mm) is the cylindrical sag. A RoC value of 266 mm (instead of the nominal 244.5 mm) was chosen after a probing test of the surface with the bonnet tool.

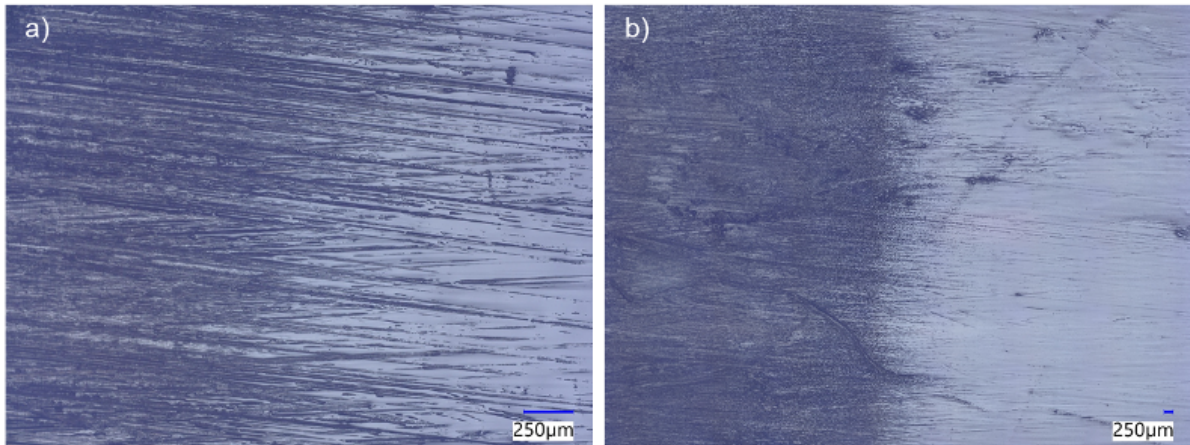


Figure 5: (a) Optical microscope image (100X) at the transition region between unpolished (left side) and polished (right side) area. (b) Microscope image with larger field of view (stitching 7×7 images with 100X magnification) covering the transition region.

residual (Figure 7). A mid-spatial frequency sinusoidal pattern with a period of ~ 4 mm to 5 mm is visible all profiles. As the azimuthal sinusoidal pattern presents in both the polished and the non-polished regions, this confirms its presence after 3D printing rather than induced from the polishing machining process.

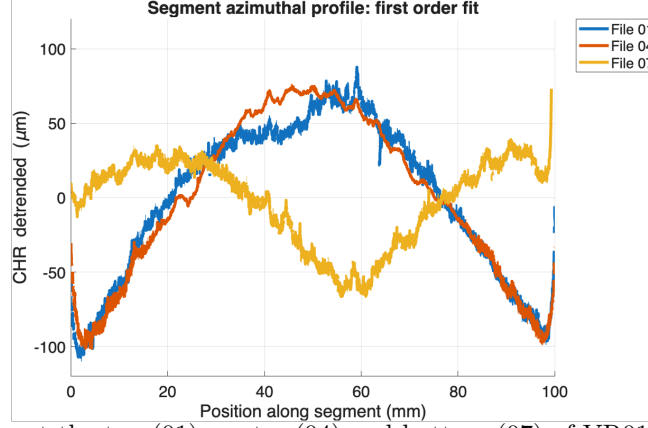


Figure 6: Azimuthal profiles at the top (01), center (04) and bottom (07) of VR01 with a 1st-order polynomial subtracted

The profiles suggest a material removal of ~ 10 μm to 20 μm at the centre of the polished area and a reduction in surface roughness, evidenced by a lower noise level compared with the unpolished profiles (Figure 7(right)). In Figure 8 the detrended profile at the centre (Profile 04) displayed in Figure 7(centre) is flipped (left to right) and superimposed on a picture of the VR01 prototype after polishing for comparison. Further polishing runs are planned in Sept. 2026 with the aim to reduce surface texture (high- to mid-spatial frequencies) and to target the surface roughness achieved on the flat samples after polishing (<1 nm Sq; Section 2.1). We hope that one output will be the removal of the printed sinusoidal pattern to allow an assessment of the expected print-through of the lattice structure due to polishing thereby validating our approach to lattice selection.

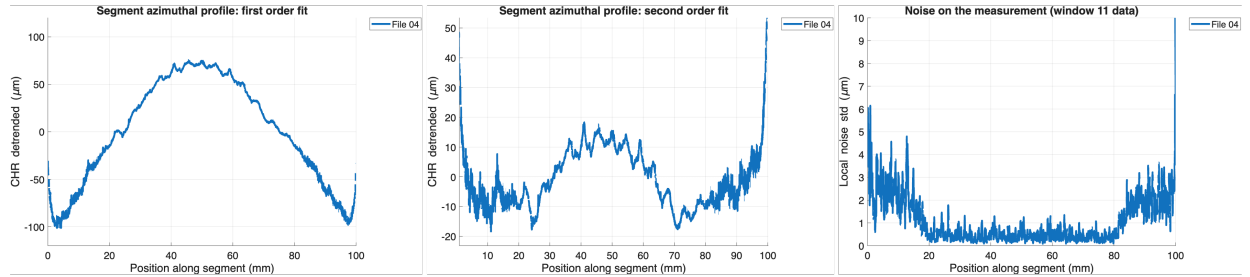


Figure 7: (left) Cleaned central profile (04) with a 1st-order polynomial subtracted; (centre) central profile with a 2nd-order polynomial subtracted; (right) Moving-window standard deviation of the shape-subtracted residual, showing how the CHR sensor noise varies with scan position independent of the surface roughness.

2.3 Outgassing rate of 3D printed fused silica

Outgassing rates for conventional fused silica are not well documented in literature;³⁴ however, the rates are accepted to be low, as evidenced by its frequent use in commercial viewports for ultra-high vacuum systems. Assuming perfect debinding and sintering processes, DLP fused silica should behave similar to conventional fused silica; an assumption supported by comparable surface roughness values measured across DLP fused silica and conventional silica glass in the study by Bissell, L. et al. 2026, sub.²⁹ We will measure the outgassing rates of the three cylindrical prototypes using the Throughput Method,³⁵ where a sample chamber is evacuated through an orifice of known conductance by a pumping chamber, the pressures of the sample and pumping chambers (ΔP) are measured and used with the conductance (C) and surface area (A) to calculate the outgassing rate

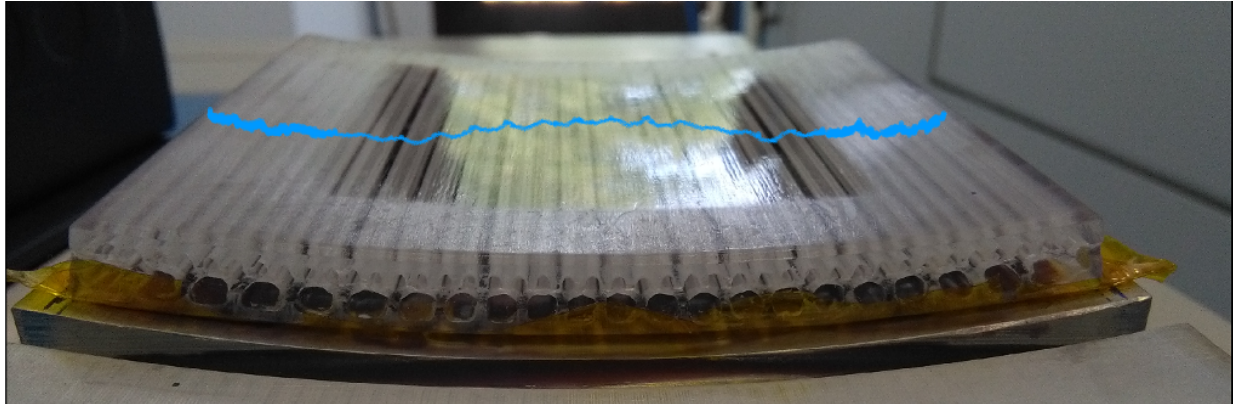


Figure 8: Profile 04 superimposed onto a VR01 picture presenting the polished 70 mm (axial) $\times$ 60 mm (azimuthal) area. The start position of Profile 04 along the segment (0 mm) is on the right side in this image.

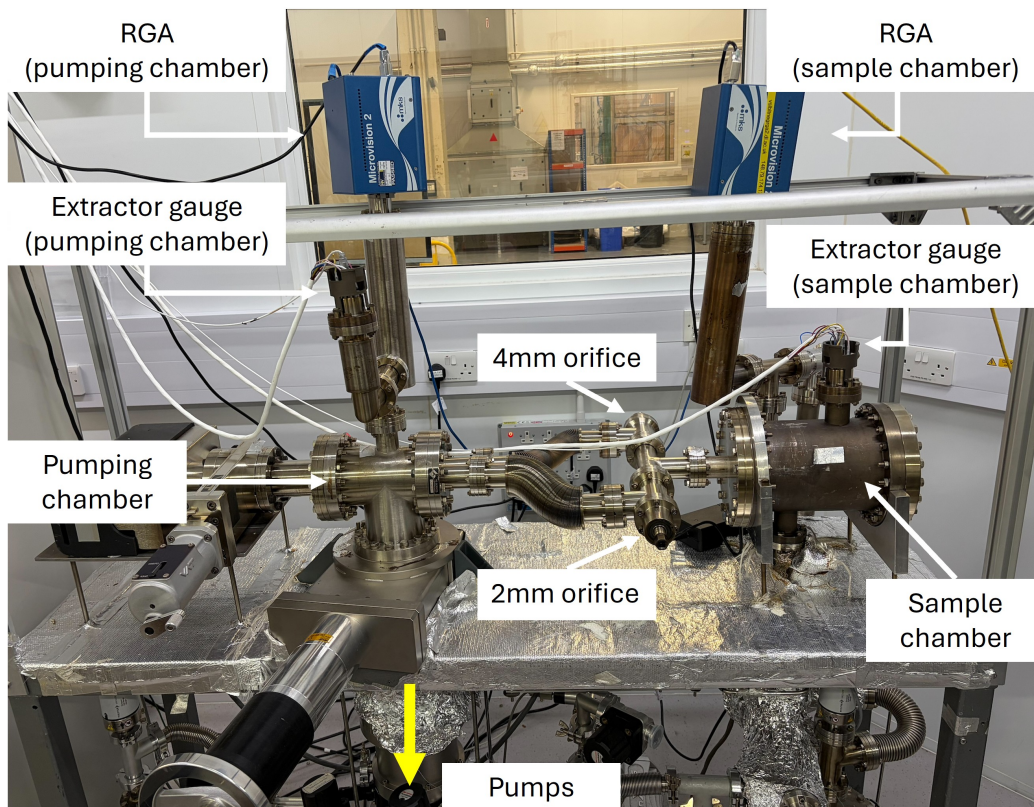


Figure 9: The STFC Daresbury Laboratory outgassing facility - Throughput Method. Image credit: R. Luff.

(Q): $Q = (\frac{\Delta P}{A})C$. A background measurement without a sample is made to separate the outgassing rate of the sample from the outgassing rate of the sample + sample chamber.

Figure 9 presents the outgassing facility used in this study. Both the sample and pumping chambers are equipped with extractor gauges to provide the pressure difference (ΔP) as well as residual gas analysers (RGAs) to identify the chemical species of the released gases. Two orifices are available, 2 mm and 4 mm, we will select the orifice following an earlier rate of rise measurement which estimates the order of magnitude of the outgassing rate. The surface area of the three prototypes range from 217.9 cm² (solid), to 581.1 cm² (TPMS), and 667.7 cm² (Voronoi), as output from the computer aided design software. Therefore, we expect that the solid prototypes will have a lower pressure rise than the latticed designs (smaller ΔP), but once surface area is considered the outgassing rate should be similar. If DLP fused silica behaves like conventional fused silica, the rate will be low, therefore, to increase the signal measured by the pressure gauges, two prototypes of each design will be measured simultaneously.

We will measure the prototypes at the STFC Daresbury Laboratory over August and September 2026 and will implement the following procedure:

1. Background outgassing measurements; no prototypes.
2. Clean the prototypes
 - (a) Pre-cleaning: demineralised water + detergent
 - (b) Cleaning: solvent HFE-72DE³⁶ (Novec™ 72DE Engineered Fluid; 3M, USA)
 - (c) Rinsing: demineralised water
 - (d) Drying: ~100 °C
3. Pre-bake outgassing measurement 1 hr and 10 hrs
4. Bakeout to 250 °C (24 hrs to 48 hrs)
5. Post-bake outgassing measurements 1 hr, 10 hrs and 100 hrs

The emphasis is placed upon the post-bake outgassing measurement (1 hrs to 100 hrs) as space hardware routinely undergoes bakeout prior to integration. Further, the European Cooperation for Space Standardisation (ECSS) lists bakeout as a requirement for thermal vacuum outgassing (ECSS-Q-ST-70-02C³⁷), but the exact temperature is material dependent. We selected 250 °C due to robustness of fused silica at high temperatures and to provide an optimum condition for the outgassing rate measurement.

3. DISCUSSION & CONCLUSION

Our OSIP study explored the potential of 3D printing in fused silica to enable a successor to the *CXO* with the vision to 3D print lightweighted full shells which are subsequently lapped and polished. The vision follows the heritage of the *CXO* mirror fabrication, but introduces digital manufacturing to reduce time and cost, and to enable intricate lattice geometries. To achieve this goal, our study investigated three themes: (1) the design optimisation, manufacture, and optical fabrication of three cylindrical prototype segments, one solid and two lightweighted, to demonstrate the ability of 3D printing to enable geometries for X-ray telescopes; (2) the suitability of DLP fused silica for X-ray reflection after lapping, polishing and pitch polishing; and (3) the suitability of DLP fused silica for high vacuum space environments determined through outgassing experiments. Although at the time of writing our OSIP study is still on-going, we draw these initial conclusions:

1. Lattice structures can be implemented to reduce mass and also optimised for X-ray reflection. When integrated within the cylindrical geometry and 3D printed, the 1 mm lattice wall thickness maintained structural integrity following the pressure exerted by the Zeeko polishing bonnet. On-going processing of VR01 iterates between polishing and metrology to evaluate the print-through of the lattice upon the would-be mirror surface and we can feedback the print-through data into our finite element analysis (FEA)

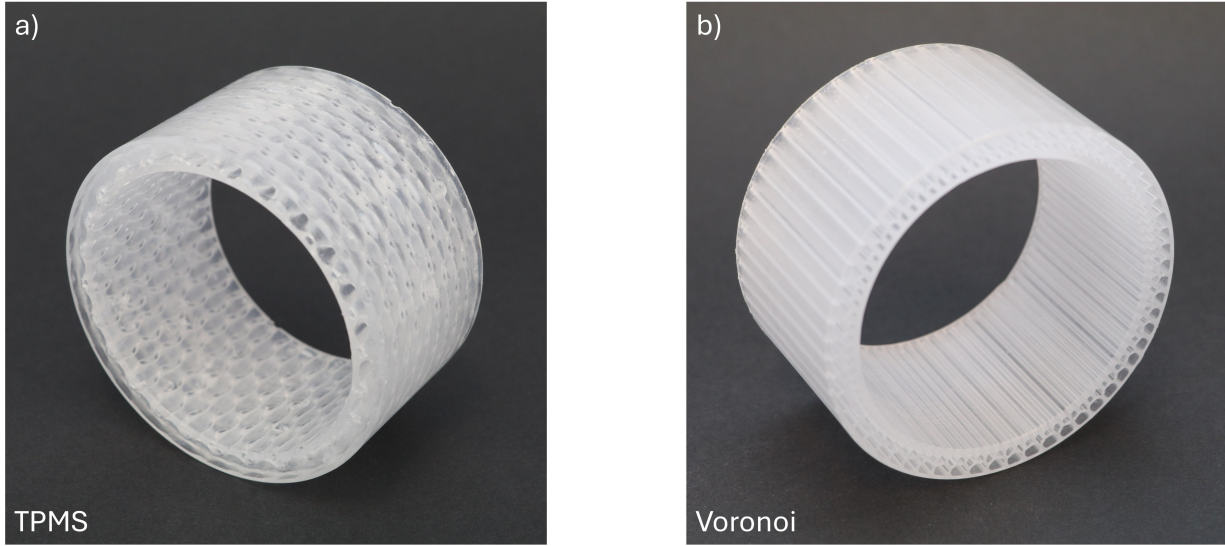


Figure 10: Example cylindrical full shell concepts (90 mm diameter, 50 mm length, and 8.5 mm thick), *left* TPMS, and *right* Voronoi. Image credit: J. Cowan, STFC.

simulations to increase the accuracy. Proposed future work investigates converting the cylindrical lattices into conic lattices to allow a second generation of prototypes that can benefit from ray-tracing simulations and X-ray testing; thereby validating our approach.

2. Surface roughness values after pitch polishing deliver $\lesssim 0.3$ nm Sq on both horizontal and vertical print orientations. On-going work will assess the X-ray reflectivity of these samples and with next steps identified to increase the X-ray reflectivity through optical coatings. Future work will transfer the successful lapping and polishing processes of the square samples on to the cylindrical segments, thereby combining X-ray reflectivity with full shell geometries.
3. Material qualification of the DLP fused silica will establish suitability for space hardware; the outgassing experiments represent the first data points in a larger qualification study. We require further materials testing to calculate true mechanical and thermal properties that can be input downstream to increase the accuracy of FEA simulations.

The identified future work leads us towards creating a 3D printed fused silica full shell X-ray mirror. Figure 10 presents a TPMS Diamond and a Voronoi full shell demonstrator and represents the maximum shell diameter possible on the DLP build plate today, 90 mm in diameter and 50 mm in height. However, VPP build volumes in polymers are available in larger dimensions approaching 1 m, therefore, the printer technology is available but it requires optimising to the specific requirements of the photopolymer resin. An advantage of 3D printing is the size of the industry, linked to the benefits it offers in numerous fields; biomedical³⁸ and aerospace³⁹ being early adopters. By leveraging the natural growth in the industry, alongside dedicated research and development for our application, 3D printed lightweight full shells in fused silica for X-ray astronomy has real potential to enable a high angular resolution, high collecting area X-ray telescope for the future.

4. DATA AVAILABILITY STATEMENT

The three cylindrical prototype .stl files described in this paper are openly available from eData the STFC Research Data repository at <https://doi.org/10.5286/edata/975>.

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