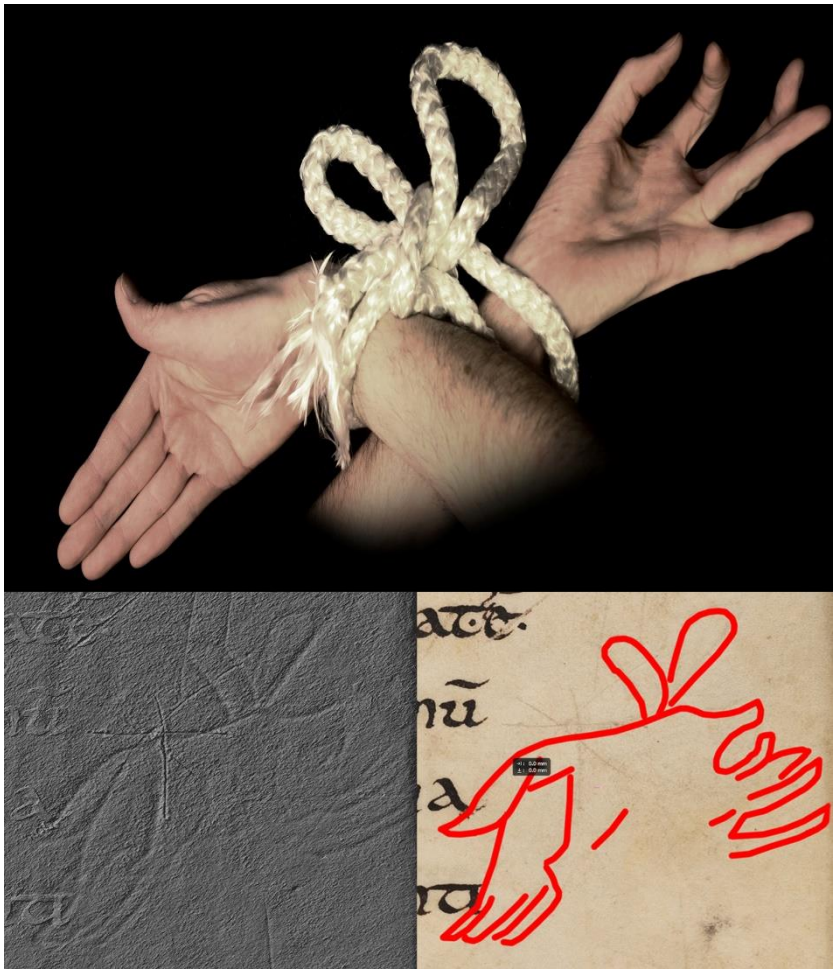
ARCHiOx

a research and development collaboration between the Bodleian Libraries, University of Oxford and the Factum Foundation

A photo-essay written by the Bodleian's Senior Photographer and ARCHiOx Technical Lead for the Bodleian, John Barrett. Assisted by Jorge Cano, and Carlos Bayod Lucini, Factum Arte and the Factum Foundation.



A hidden marginal annotation, inspired by Chapter 22:14 from the Gospel of Matthew – revealed through 3D imaging. MS. Laud Misc. 429.

ARCHiOx is a research and development project which uses technology conceived and developed by the Factum Foundation to record the three-dimensional surface of originals from the Bodleian Libraries collections. The Bodleian is the first institution in the world to use a newly developed prototype 3D recording system named the Selene. This state-of-the-art technology is capable of

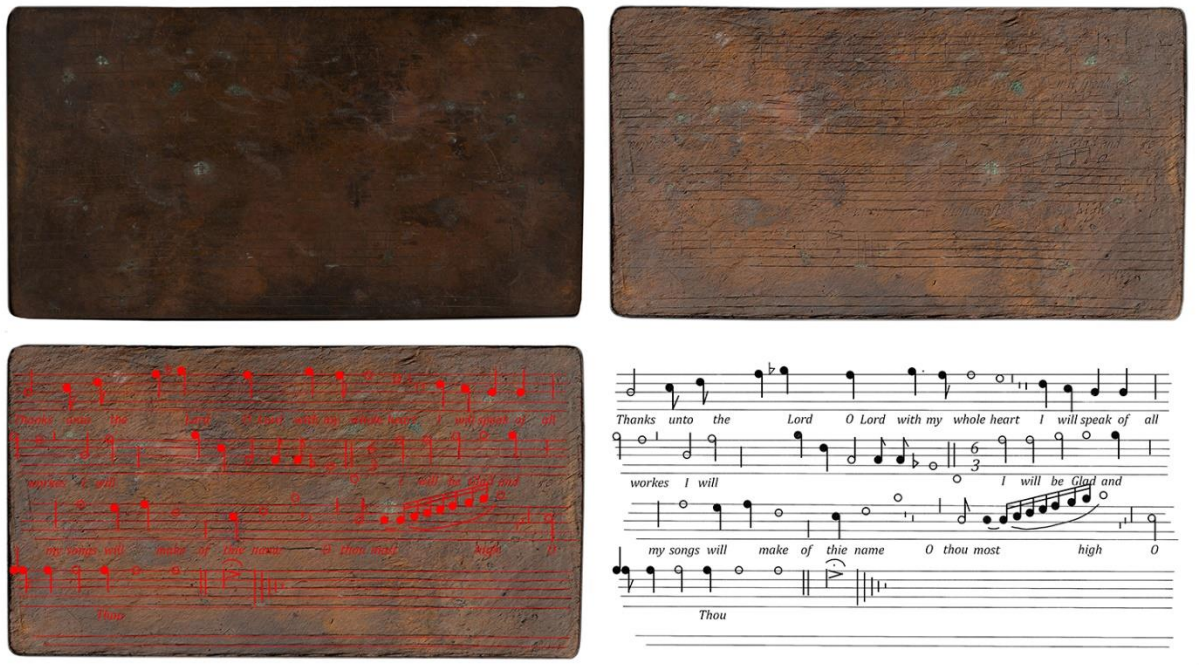
capturing originals at a resolution of one million pixels per square inch, and recording height variation equivalent to less than a quarter of the width of a human hair. Recordings made with the Selene serve two purposes: The data can be used to create renders which show the 3D surface of an original in order to reveal what is difficult or impossible to record through conventional photography, or for the purposes of creating incredibly accurate 3D facsimiles.

Printing surfaces

Very little is known about the small copper printing plate below. Thought to have been made in the early eighteenth century, the engraved portrait depicts Cardinal Julio Mazarin. During the mid-17th century, Mazarin was Minister to Louis XIII and Louis XIV of France. In the 300 years since it was engraved the plate has become heavily corroded making the design extremely difficult to see. But by creating a render; a 2D image which shows only the 3D surface of the plate in the absence of its tone and colour, the design has been revealed in astonishing detail.

A small copper printing plate featuring a portrait of Cardinal Mazarin. Left: a conventional colour image. Right: a shaded render created from 3D data recorded from the original's surface. Rawl. Copperplates g.184.

What makes this printing plate particularly intriguing is that it has been re-used, and bears designs on both front and back. This is not uncommon. The Mazarin portrait plate is one of many examples of reused printing plates within the Bodleian's collections. Once turned, it may be possible to make out evidence of a design, but little more than a few horizontal lines. The 3D recording of this side of the plate has revealed what is very difficult to see, and would be impossible to photograph conventionally. The horizontal lines are in fact musical staves under which are written the words to a piece of music. Through enhancing and mirroring the render it has been possible to decipher the position and measure of every musical note. Digital annotations of the words reveal that the piece was likely to have been inspired by verses 1-2 of Psalm 9. This new discovery, made possible through 3D recording, can for the first time be documented in the catalogue description for this small printing plate.



The shallow etching on the reverse of the Cardinal Mazarin printing plate has been revealed through 3D recording. Every musical note has been identified and transcribed, along with words thought to have been inspired by Psalm 9. Top right: colour image Top left: a composite image made from a 3D render and albedo. Bottom left: a digitally annotated version. Bottom right: digital annotations with the image removed. Rawl. Copperplates g.184.

I will give thanks to you, Lord, with all my heart;

I will tell of all your wonderful deeds.
I will be glad and rejoice in you;
I will sing the praises of your name, O most high.

Psalm 9:1-2, New International Version

This example is one of dozens of copper printing plates from the Bodleian's Rawlinson and Gough collections that have now been recorded. Notoriously difficult to capture using traditional photographic techniques, copper printing plates were the first category of originals to be recorded for the for ARCHiOx. The effectiveness of the Selene photometric stereo recording system was immediately apparent. These 3D recordings continue to amaze visitors to the Bodleian's Imaging Services Studio. Designer of the Selene, Jorge Cano recalls his reaction when seeing the first ARCHiOx recordings.

"I remember with particular excitement the first day I saw the scan results on the copper plates from the Rawlinson Collection. Thanks to the high-resolution surface recording from the Selene Photometric Stereo Scanner, we were able to see every detail of the engravings that the artist had made by hand on the surface of the metal, details that were previously hidden under years of dust and rust. It was as if the plate came to life in front of us, allowing us to see it with new eyes and discover information and beauty that had previously been hidden. I believe that high-resolution surface recording technology is an innovative and exciting way to breathe new life into ancient objects and to promote culture and history for future generations." Jorge Cano, Head of Technology, Factum Foundation and Factum Arte.

Prints on paper

A mid-19th century woodblock print illustrated by Gosōtei Hirosada. Left: albedo colour image. Right: greyscale shaded render of the 3D surface. Nipponica 372.

But it's not just printing *plates* that have been recorded for ARCHiOx. Recordings of the prints themselves also reveal details which are almost impossible to see. The beautiful Japanese Ukiyo-e woodblock print above is featured in an album illustrated by Gosōtei Hirosada (fl. 1826–63) and published in Osaka during the mid-late ninetieth century by Kinkadō Konishi. In addition to the application of coloured pigments, the printer has used other techniques such as blind printing and burnishing to add textural elements to the print. The render clearly shows the impressions in the surface of the paper, having been pushed down onto the woodblock from above. It also allows us to appreciate the intricate decoration in the clothing of the kabuki actor with a level of detail which is almost impossible to achieve when studying the print or looking at standard digital images alone.

3D recording has not only allowed us to see these decorative elements more clearly, they have also assisted with research into the production of the prints. Through the ability to examine profiles through the impressions and to take measurements, in some cases it is possible to determine the

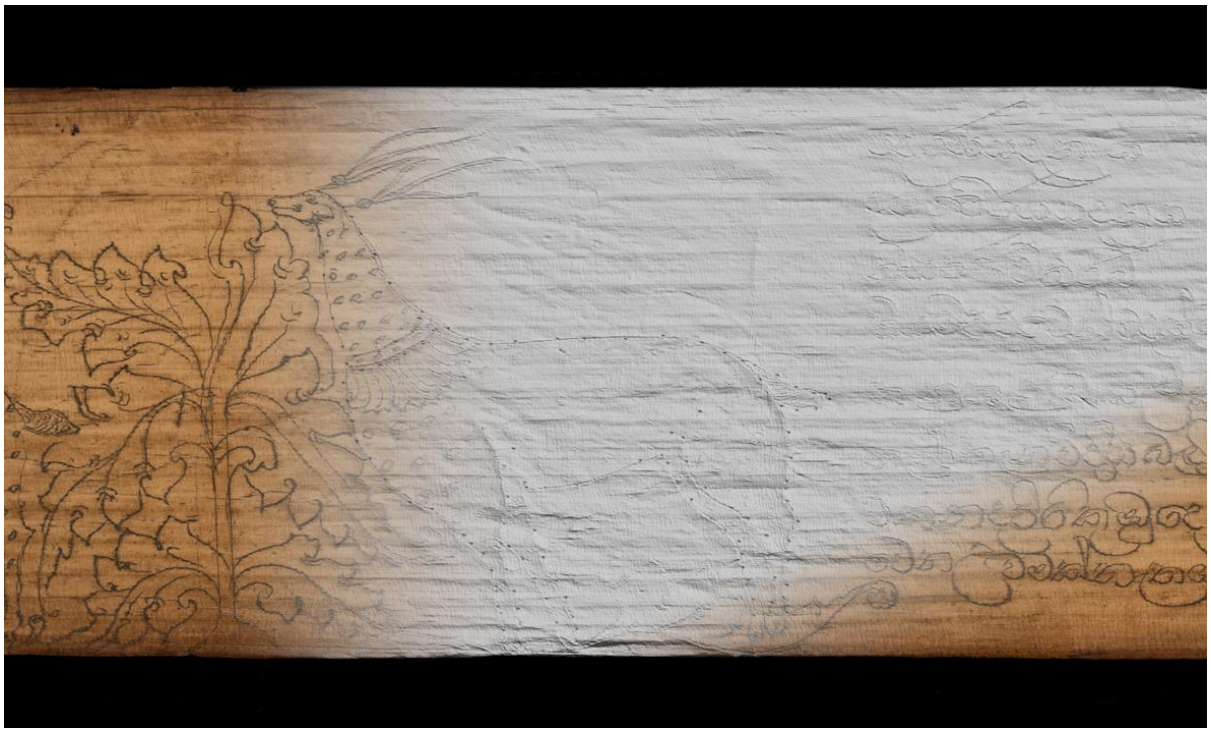
sequence of processes which the printer would have followed. This innovative method of analysis has been explored by Manager of the Japanese Library and Curator of Japanese Rare Books and Manuscripts at the Bodleian Libraries, Alessandro Bianchi.

> *"The technology developed by the Factum Foundation and tested at the Bodleian Libraries as part of the ARCHiOX project enabled us to examine Japanese prints in a completely new way. We can now digitally gather new material evidence that can help us better understand the manufacturing process of each print. More broadly, in the future this technology could be greatly beneficial to aid researchers working on the material production of artefacts, to enhance remote consultation of collection items, and even to promote long-distance collaborations with scholars from across the globe."* Alessandro Bianchi, Manager of the Japanese Library and Curator of Japanese Rare Books and Manuscripts, Bodleian Libraries.

An example from an album of Mughal Indian paintings and calligraphy, from the Shahjahan period. Lower left: the 3D render reveals indentations and decorative elements not recorded in the colour image. MS. Douce Or. a. 1.

Painted pages

The beautiful painted page shown in the image above belongs to a 17th century album, made in the Mughal Empire. The recording made with the Selene not only shows the individual layers of paint which have been applied to the paper, but also hundreds of tiny pricked holes which cannot be seen in the colour image. In this example, holes have been used purely for decoration, enhancing reflections in areas where shell-gold has been applied.

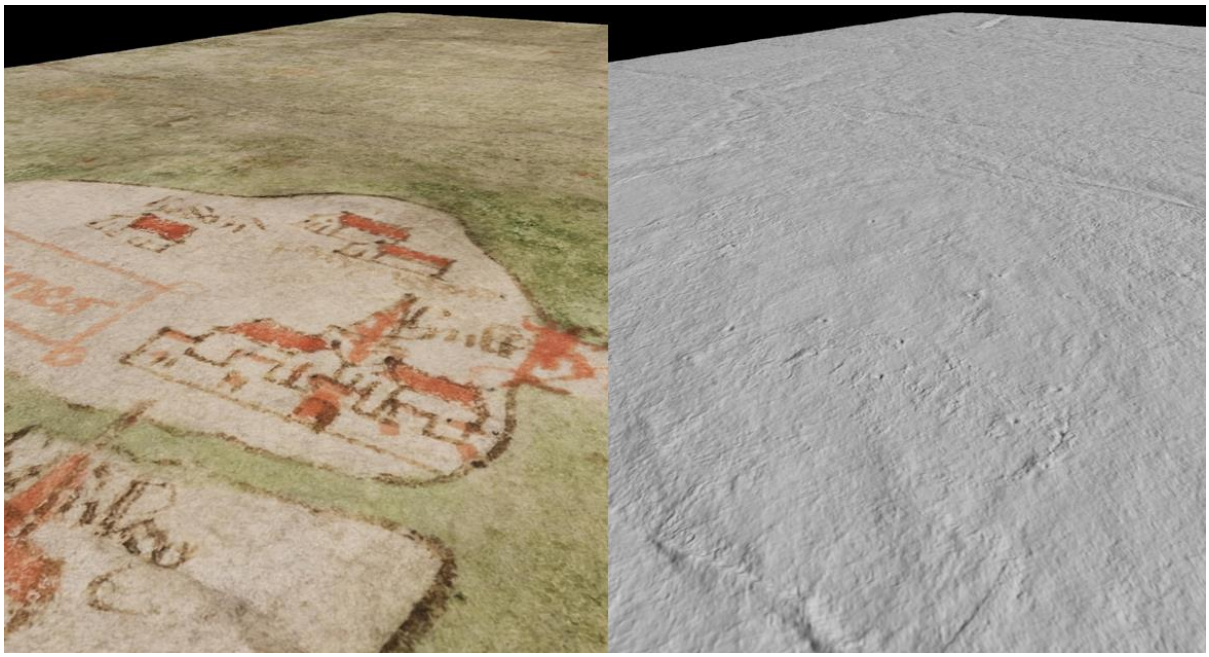


A palm-leaf with incised manuscript and illustration. The render made from the 3D recording has revealed the presence of tiny pinholes, evidence that the design was either made using a copying technique or itself used to create copies. MS. Sinh. b. 27.

By contrast the image above demonstrates how pricking is likely to have served as a means of copying. In this case the outline of the deer has been pricked, suggesting that the design has either been transferred from an earlier illustration or may have been used to generate others. The render also shows that the Sinhalese text from this palm-leaf folio has been incised using an iron stylus or reed pen before being inked. Among examples of incised palm-leaf manuscripts from the Bodleian's collections are similar texts which have not been inked, making them difficult to read. 3D renders have been generated from these examples and are extremely effective in revealing this hidden text.

A 14th-century map and a modern facsimile

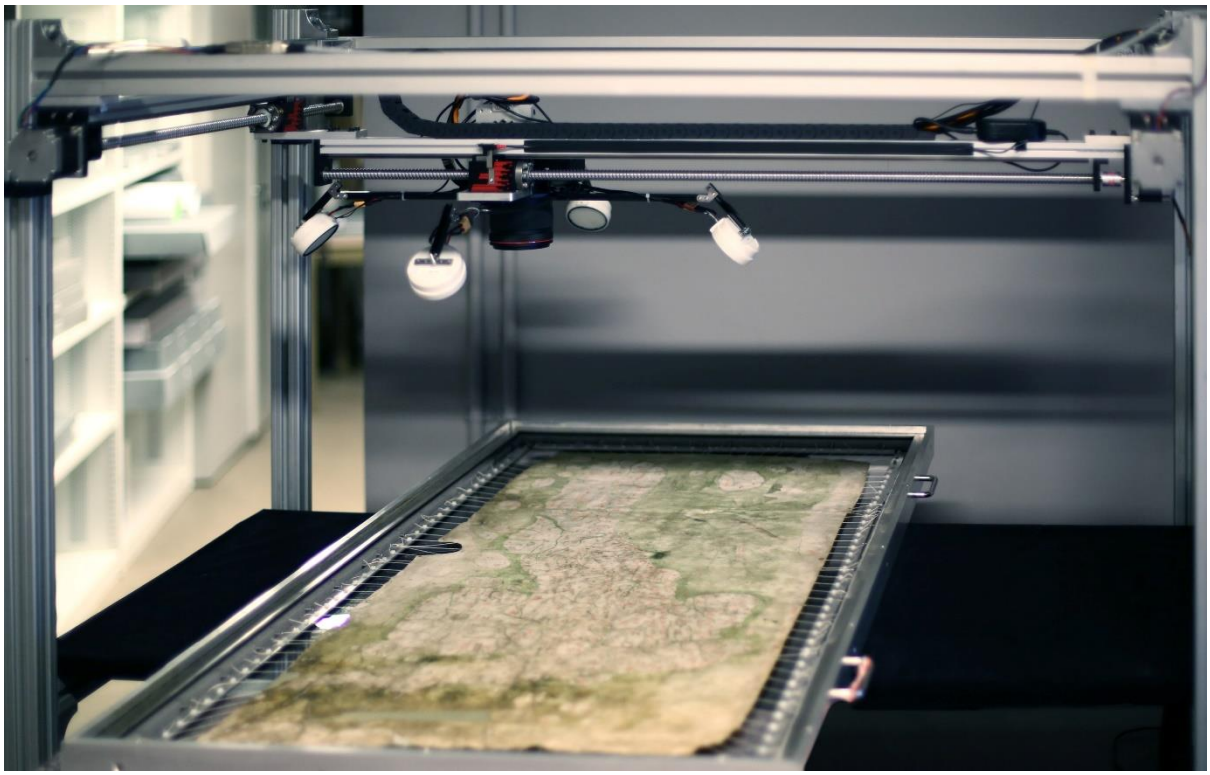
The process of copying using pinholes is also evident on the largest original which has so far been captured for the project. Dating to the 14th century, the Gough Map is one of the earliest maps to show Great Britain in a geographically recognisable form and served as a blueprint for maps of Britain for over 150 years. Bequeathed to the Bodleian Library by Richard Gough (1735-1809), the map is covered in over two-thousand tiny indentations which transferred the position and form of geographical features from a precursor map. Through studying these pinholes, researchers may be able to determine which features would have been present on the precursor map and in doing so, estimate when it may have been made.



Oblique images of the sign marking the location of Hull, East Yorkshire. Left: albedo. Right: shaded render showing the micro topography of this area of the map, in the absence of the original's colour. Tiny indentations marking the form of the sign provide evidence that the map was copied from a precursor map. MS. Gough Gen. Top. 16.

This historic map has been recorded numerous times since its creation. It therefore serves as wonderful case-study in the development of copying and imaging techniques. A copper printing plate was engraved in 1780, prints from which are held in the Bodleian's collections. Using a novel reproduction method developed at the Ordnance Survey, a photozincography recording was made in 1871. In 1958, a run of collotype prints of the Gough Map were made at Oxford University Press. The map was recorded digitally for the first time in 2006. Hyperspectral and 3D laser recordings followed nine years later, in 2015. These initial 3D recordings were conducted by the Factum Foundation's Head of 3D scanning, Carlos Bayod.

> *"The recording carried out in 2015 applied the Lucida 3D Scanner to capture for the first time the topographical characteristics of this unique map. One of the first collaborations between the Bodleian Libraries and Factum Foundation, this survey allowed us to see and measure the shape and surface of the map without the colour layer, making it much easier to allocate the distribution of the pinholes, among other marks present on the relief. The information captured by the Lucida systems offers the possibility of visualizing the map's surface on-screen as a shaded render, an image format onto which it is possible to register other layers of information such as the colour photographs. Additionally, it creates a greyscale depth map that can be used for re-materializing the data as an accurate physical reconstruction, becoming the base for creating an exact facsimile".* Carlos Bayod Lucini, Head of 3D Scanning, Factum Foundation



The new photometric stereo recording of the Gough Map captured with the Selene, was captured in June, 2022. MS. Gough Gen. Top. 16.

The photometric stereo captures made for ARCHiOx, are the highest resolution recordings of the Gough Map to date. Both the front and reverse of the map were recorded at over 700,000 pixels per square inch. In order to record the map at this resolution, 85 image tiles were captured, processed and stitched together to form a single image. Prominent pinholes and scoring marks are clearly visible from the recordings. These have been analysed, using geographical information system software by Damien Bove, Researcher for The Gough Map Project and Picture Editor of Imago Mundi: International Journal for the History of Cartography

> *"The pricking on the Gough Map is key to its creation, marking the location and form of place signs copied through from a precursor map. Where the tool has been pressed through the skin, it has left holes. Most of these can be seen on high resolution photos and on the earlier Lucida scan. Where the tool was pressed with less force, however, it has left only small depressions. The ARCHiOx scan has allowed us to identify and measure these for the first time, giving us a fuller understanding of the earlier map."* Damien Bove, Researcher for The Gough Map Project and Picture Editor of Imago Mundi: International Journal for the History of Cartography.

But the ARCHiOx recording has not only allowed for on-screen analysis. The data has also been used to create a remarkably accurate three-dimensional facsimile of the map. Currently installed in the Bodleian's Map Room, the facsimile provides an opportunity for close examination, ensuring that the original map need not be as frequently transported or removed from its protective casing.

Visitors examine a three-dimensional facsimile of the Gough Map, made by Factum Arte, following a presentation given by the Bodleian's Map Curator, Nick Millea.

> *"Facsimiles allow us to have a more natural connection with valuable cultural objects. Thanks to the possibility of reproducing the surface relief and colour in high resolution, a facsimile can serve a triple function contributing to the preservation, study, and dissemination of the original, for the benefit of both experts and amateurs alike".* Carlos Bayod Lucini, Head of 3D Scanning, Factum Foundation

Paintings and preparation

The Laud Ragamala Album is a beautifully painted South Asian manuscript, dating from the early 17th century. Relatively shortly after it was produced, the volume was donated to the Bodleian by Archbishop William Laud, at some point between 1635-41. It has been proposed that that three, recently discovered paper pouncing patterns may have been used in the production of paintings from the manuscript. The patterns, which have subsequently been loaned to the Bodleian, are skilfully made. Tiny pin-pricks forming the outline of illustrations which are clearly recognisable with three of the paintings from the Laud Ragamala Album. Pouncing is a less obvious method of copying than pricking. Charcoal dust would have been transferred though the holes, duplicating the form of a design from pattern to page. Whether or not the three pouncing patterns were indeed the source of the paintings from the Bodleian's 17th century volume remains somewhat of a mystery. In order to examine how closely the two align, a set of renders were generated from 3D recordings of the pouncing patterns and overlaid with the colour images from the manuscript.

Left: a paper pouncing pattern, photographed conventionally. Centre: an edited version of the previous image showing the position of the tiny pinholes. Right: A detail from fol. 8 of the Laud Ragamala Album. MS. Laud Or. 149.

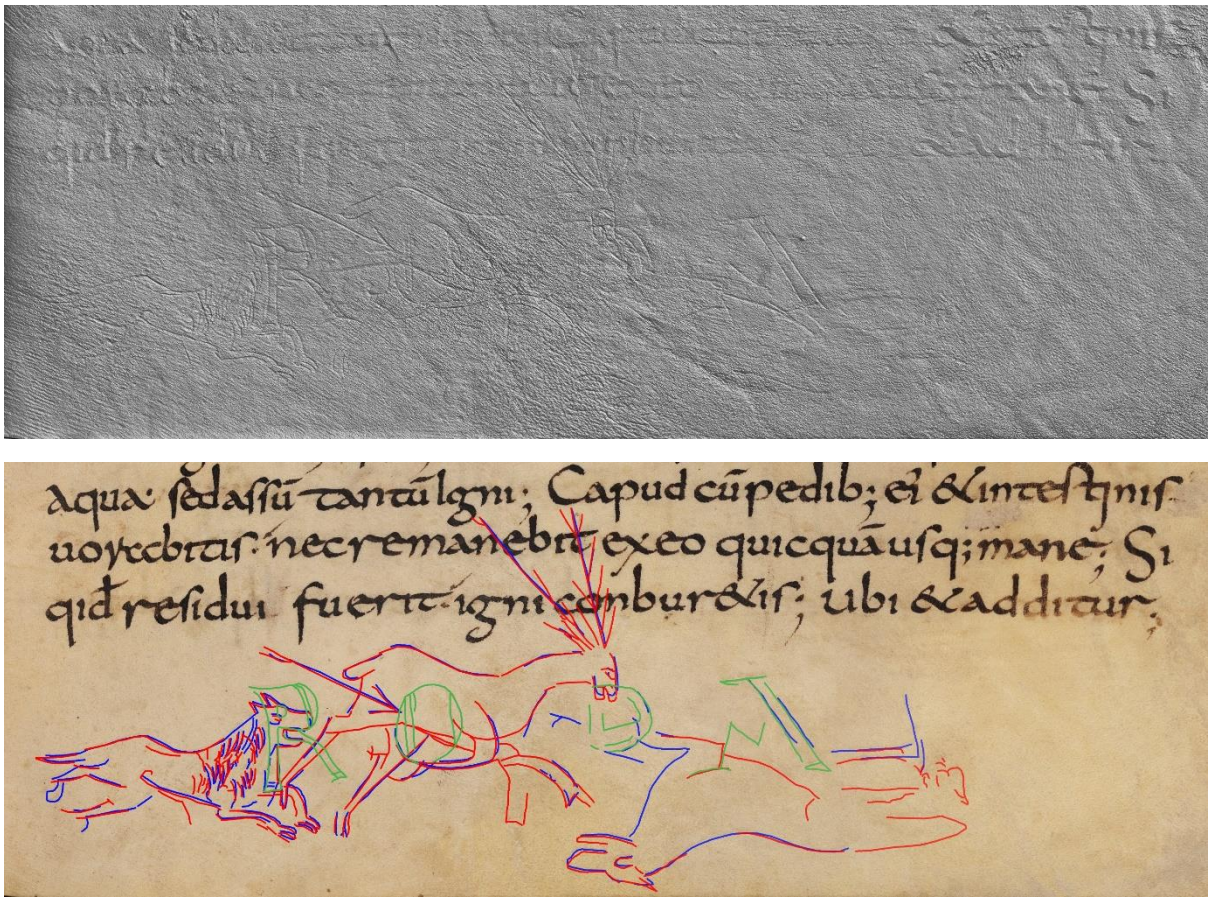
Though some elements within the designs differ, there is a clear and extremely close correlation between the patterns and paintings. 3D imaging of the paintings themselves show no evidence of holes or depressions due to tracing, only the layers of pigment which have been applied to the paper. Though the 3D recordings have not provided a definitive answer as to whether the patterns may be the origin of the paintings, it is hoped that they may serve as a template for similar analysis.

A layered image comprising of: Left: a painted page from the Laud Ragamala Album. Right: a mirrored heat-map render of the verso of the corresponding pouncing pattern. Centre: a composite of the left and right images. MS. Laud Or. 149.

A 9th century insular manuscript, Gregory the Great, Homiliae XL in evangelia. MS. Laud Misc. 429.

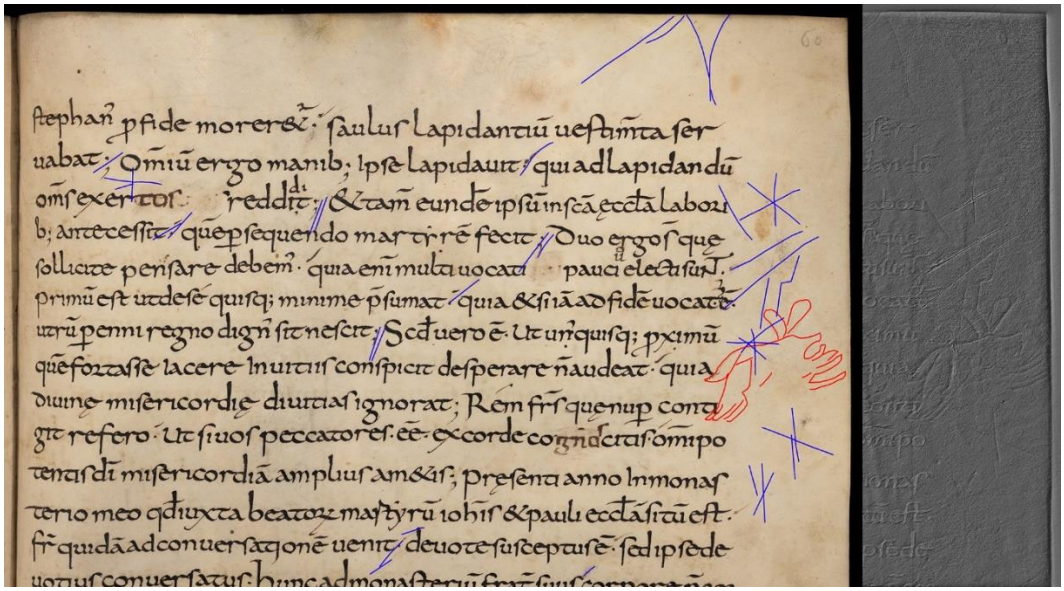
A 9th-century manuscript and stories in the margin

The above manuscript, Gregory the Great, Homiliae XL in evangelia, is written in Latin and dates to the first half of the 9th century. The 15th century shelfmark on folio 2, reveals that this volume was in the possession of the cathedral church of St. Kilian in Würzburg. Examples of annotations made not in ink, but through scratching the surface of the parchment using a drypoint stylus have now been discovered and recorded on twenty-five pages from this volume, using the Selene. The catalogue description for the recto of folio 74 shown in the image above, describes a drawing in the lower margin. A hunting scene, barely visible from the conventional photographic recording, but clear enough to make a partial digital annotation. Far more successful at revealing the inscription, the 3D render shows not only the illustration, but also four camouflaged letters, *R, O, D, A.* This demonstrates how 3D recording can compliment traditional imaging in revealing and documenting new discoveries.



Top: a shaded render of a drypoint addition from the lower margin of folio 74r. Bottom: a compiled digital annotation using conventional and 3D recordings, showing the position and form of the addition. MS. Laud Misc. 429.

The drypoint annotations recorded on folio 60r, in the image below, are inconsistent with the majority of others from this manuscript. These have been added between passages of text rather than confined to the margins. In this example, relatively deep incisions have been made, marking the position of punctuation. Far less obvious and perhaps only recognisable from the 3D render is a small, marginal illustration showing two hands, tied together with a bow.



A digital annotation from folio 60r, showing numerous drypoint additions. MS. Laud Misc. 429.

In order to determine whether or how this annotation might relate to the text, the image above was shared with Jo Story, Professor of Early Medieval History, Leicester University. Her interpretation reveals a clear link between annotation and text. The text from this homily describes the stoning of Stephen. The translation of folio 60r begins *'when Stephen was dying for his faith, Saul kept the clothes of the stoners. Therefore, he himself stoned them all with his own hands, who returned all the works to the stoners.'* The connection between inscription and text is most evident from the passage at the end of the fourth line *'Duo ergo sunt que' – 'because many are called but few are chosen'* - Chapter 22:14 from the Gospel of Matthew. This passage immediately follows the verse '*Then said the king to the servants, Bind him hand and foot, and take him away, and cast him into outer darkness, there shall be weeping and gnashing of teeth.'*

Dozens of similar recordings of unlinked manuscript annotations have now been captured using ARCHiOx technology. The discovery of the name 'Eadburg' from another of the Bodleian's early medieval manuscripts by PhD candidate Jessica Hodgkinson is described in *a previous Conveyor post.* Recordings from these two manuscripts have demonstrated that photometric stereo recording is extremely effective and is likely to hold the key to documenting incised markings from similar volumes. Revealing these markings which have remained undetected for centuries is an incredibly exciting application of this new technology.

> *"The new photometric stereo recording methods that are being pioneered by John and the ARCHiOX team are transformative. The method allows us to see the surface of the pages in much greater detail than ever before and will give us insights into the preparation of the membrane and the methods used to make the quires, as well as acts of reading and engagement with the book after it was completed. New, and almost invisible, marks are now easily seen – revealing huge amounts of new information about medieval book culture – and the people who made and read them. This changes what we can do, the questions we can ask, and the answers that are revealed."* Jo Story, Professor of Early Medieval History, Leicester University.

Centre: Carlos Bayod Lucini, Head of 3D Scanning for the Factum Foundation. Left and Right: Richard Allen and Andy Irving, Bodleian Digital Library Systems and Services. Factum Arte, Madrid, 2022.

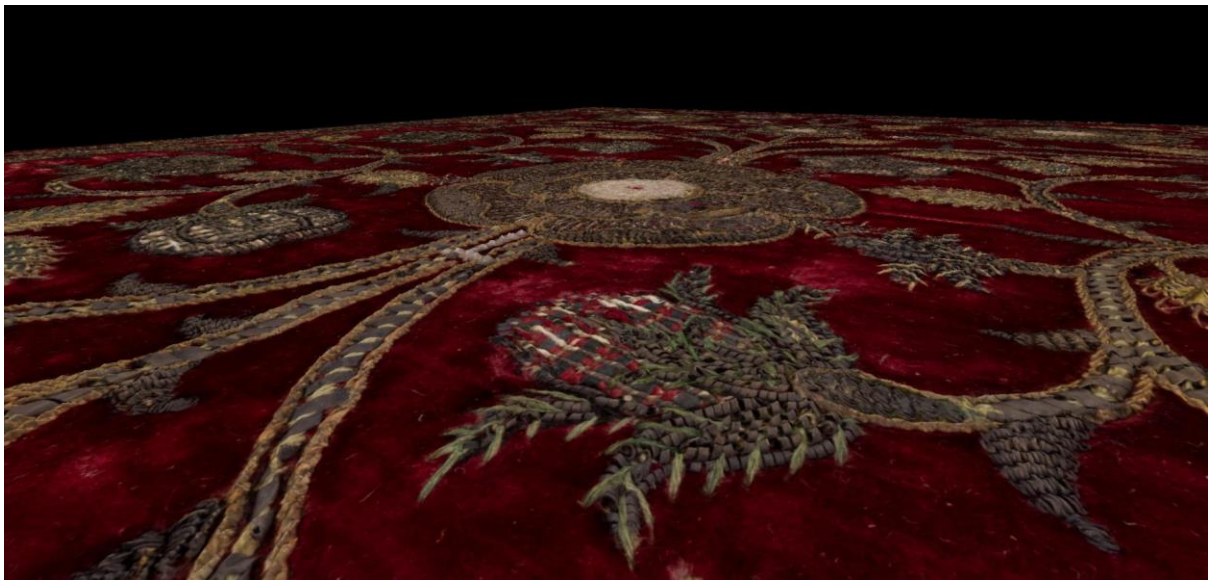
An embroidered binding

The beautifully bound 16th century Bible shown below is one of the Bodleian Library's treasures. Presented to Elizabeth I in 1584, this Bible was bequeathed to the Bodleian by Frances Douce in 1834. The incredibly intricate embroidered design features Tudor roses on a crimson velvet background. Despite its fragility this 400-year-old binding is surprisingly well preserved, but given its importance, access to the original is understandably limited.

The embroidered binding of a Geneva Bible, owned by Elizabeth I. Douce Bib. Eng. 1583 b. 1.

Even the very best conventional photography provides only a static, single perspective of an original. 3D imaging however, may allow researchers a far closer experience to handling the original than would be permitted.

Created with the Selene, the new photometric stereo recording has captured every stitch and embroidered element from the original, even its tiny seed pearls. Rather than simply making a render of the 3D surface, by loading both the depth map and albedo (colour) image into mapping software, it is possible to zoom-in, fly over the surface of the recording and relight it from any direction or height.



A screen capture of the photometric stereo recording, displayed using a 3D viewer in GIS software. Douce Bib. Eng. 1583 b. 1.

But being able to interact with high-resolution 3D digital recordings is limited by the processing capabilities of the applications or browsers being used to display them and the computer hardware on which they run. For the ARCHiOx photometric stereo recordings this limitation has been partially abated due to the way in which the 3D data is stored. 2D images which store 3D data, known as *raster maps* are at the heart of the Selene photometric stereo workflow developed by Jorge Cano. Simulations and rendering are achieved far more efficiently using raster maps than through more commonplace 3D methods, which use a wire-frame mesh model. For recordings made at an equal resolution, the file-size of a raster map is between ten to twenty times smaller than a 3D recording stored using a polygonal mesh model. It is this that makes it possible to generate and display 3D recordings of highly textured originals at such an impressive resolution. Recordings made in this way are capable of capturing the material nature of the original as perfectly as technology will allow. But further development is necessary in order to streamline the processing required to produce these raster maps.

> *"Right now, we're in a sweet spot that's also exciting: seeing the good results that we've been working towards for several years is a powerful motivator to keep going. At the same time, we know that there's a lot of software development and testing ahead of us. The processing pipeline is made up of different parts, each of which is handled by different software, and our goal is to unify it all into a single open-source software."* Jorge Cano, Head of Technology, Factum Foundation and Factum Arte.

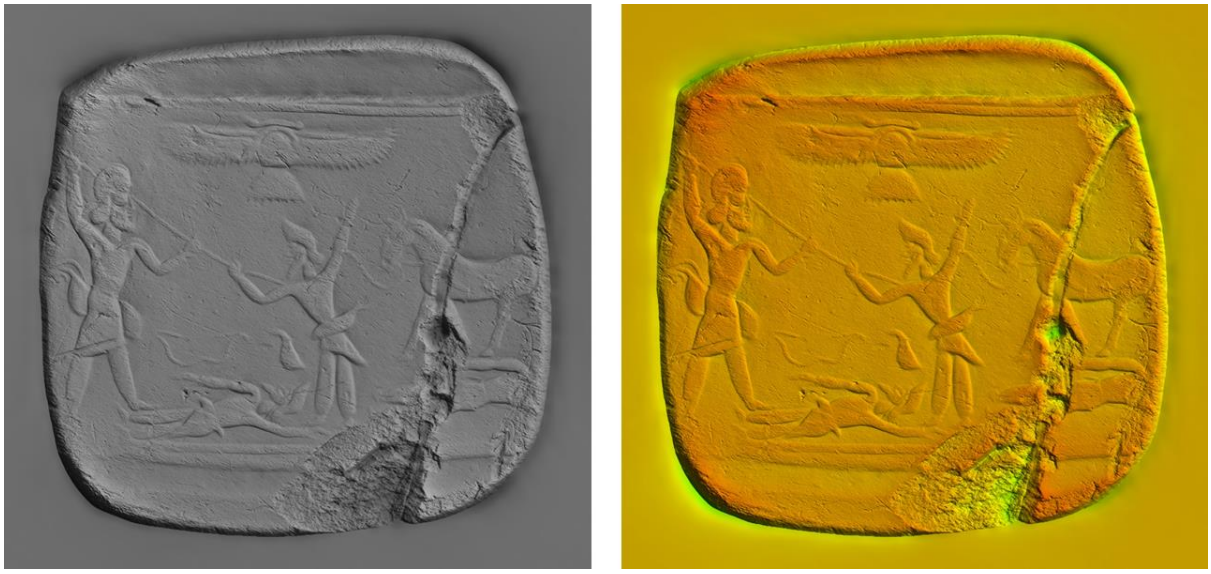
Left: Jorge Cano, designer of the Selene and Head of Technology for Factum Arte and Factum Foundation. Right: Richard Allen, Software Engineer, Bodleian Digital Library Systems and Services. Factum Arte, Madrid, 2022.

Clay letter-seals of the Achaemenid Empire

By far the earliest collection of originals to be recorded for the project originate from the Achaemenid Empire, and date to between 500 and 400BC. The following image shows a clay seal, or letter-bulla, bearing the impression of the seal of Aršāma, a Persian prince and regional governor. It is one of eight seals, which would have accompanied letters sent to the steward of Aršāma's estates in Egypt. The impression made on this example, and six other bullae from the collection were made using the same cylindrical seal. Lost to time, this incredibly intricately carved tool would have been rolled over the surface of each of these tiny clay seals, which measure little more than four centimetres. The clay which forms these seals is unfired and consequently these small originals are incredibly fragile. In some cases, the seals are held together by the string which would have attached them to the letters they accompanied. Recording such vulnerable originals is of great importance to ensure their preservation.

An impression of the seal of Aršāma from Sigill. Aram. V.

Capturing small originals like these seals with the Selene in order to make renders is a reasonably straight-forward and quick process. In the left-hand example below, the shaded representation of the recorded surface has been generated by positioning a virtual light source at 60 degrees from the surface on which the original rests. In addition, other shaders can be applied, as shown in the right-hand example, which uses a spectrum of colour to represent height.



A different perspective. Two renders of the surface of Sigill. Aram. VIII made with data recorded with from the Selene. Left: a greyscale shaded render. Right: a heat map, using a spectrum of colour to represent variations in height.

The Selene is capable of recording at over one-million pixels per square inch. This resolution is entirely adequate for capturing the majority of the Library's originals, but for recording such tiny items an alternative approach has been taken. Instead of using the Selene, a one-hundred-megapixel medium format digital camera has been used to photograph the four source images. In place of the custom flash modules, each seal has been illuminated using a studio flash unit. Mimicking the Selene's operation, having captured the initial source image, the flash unit is moved to an equidistant position to the original at 90 degrees from the previous location, and the process repeated.

Combining focus-stacking and photometric stereo. Though the thickness of the seal is a mere 7.5mm, limited depth-of-field due to recording at such a high magnification only allows for acceptably sharp capture of the top 2mm. The benefits of focus stacking are particularly notable at the edges of the seal as they taper down. Left: single exposure. Right: focus-stacked image. Sigill. Aram. V.

Recording the seals in this way has made it possible to capture them at over six and a half million pixels per square inch, but at this resolution the depth of field is extremely shallow. Focus stacking is a technique whereby multiple images are photographed from a static position with an incremental adjustment made to the focus between exposures. The resulting stacks of images are then combined in software. In this way the depth-of-field is extended and the recording appears absolutely sharp from top to bottom. Perfect alignment of the four focus-stacked source images to enable photometric stereo processing is the most challenging element within the process.

A screen-capture of the 3D recording of Sigill. Aram. V, viewed in GIS software.

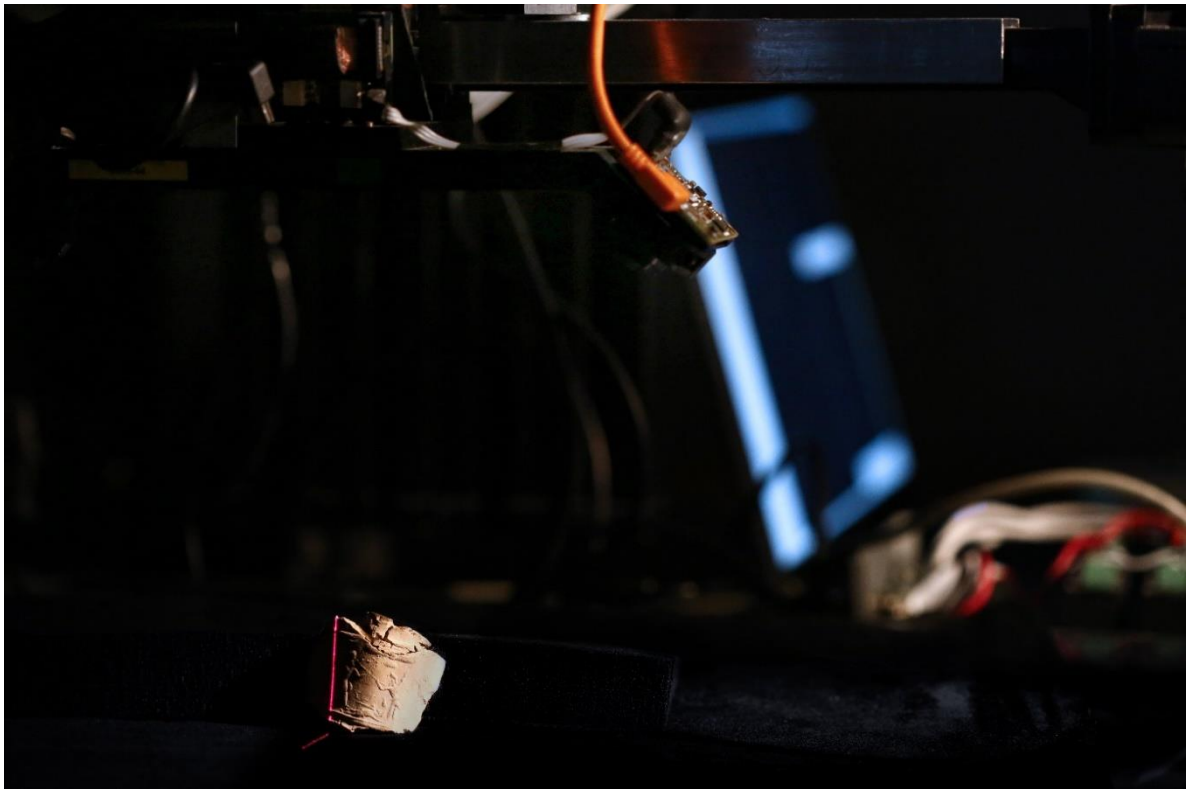
The final recordings are incredibly impressive. Every tiny detail of the impression, historic repair and even the fingerprints of the maker are clearly visible. These features can be explored using a 3D viewer within GIS software. Moving over the surface of the recording is similar to flying over the surface of a desert landscape, where each granular element becomes a geographical feature. This new method of recording represents an important advance in imaging for the purposes of preservation. The recordings of the seals will allow researchers to study originals in a way that has never before been possible.

3D views of the reverse of Sigill. Aram. VIII. The wonderfully preserved string from this letter bulla still holds a fragment of parchment from one of the letters to which it was originally attached.

The image below shows one of the fourteen parchment letters from the Aršāma collection. The Aramaic text is reasonably well preserved, and has been almost fully transcribed. The letter suggests that Aršāma valued not only horses, two of which feature on his seal, but also three-dimensional artworks. Addressed to Nakhthor, the steward of his estates in Egypt, Aršāma commissions the production of statues to be made by a sculptor believed to be Hinzani.

A letter addressed by Aršāma, Persian Satrap of Egypt to Nakhthor the steward of his estates in Egypt. An excerpt of the text is translated as follows. …'And let him make statues (on) which there shall be horsemen (?), and let him make a statue of a horse with its rider, just as previously he made before me, and other statues. And send (them), and let them bring (them) to me at once, with haste'… Pell. Aram. III.

So it seems fitting, that we should carry out Aršāma's request, albeit two and a half millennia later. Producing a scaled-up three-dimensional facsimile of the fifth seal using the data recorded with ARCHiOx technology. Firstly, the Lucida scanner was used to record the general shape of the seal from each orientation. This volumetric data provided a base, over which the higher resolution, higher frequency data recorded with the Selene could be overlaid.



The Lucida uses a projected laser line and two tiny cameras to record the form of each surface of the seal. Sigill. Aram. V.

With the photometric stereo and laser recordings combined, elevated printing was then used to construct the facsimiles at four times the original size. Several variations were made in order to assess which might be most useful for the purposes of study. Firstly, an uncoloured version was made, showing only the volume of the seal. Two coloured versions followed, the first printed with a shaded render in order to enhance the debossed design, and the second printed with the albedo (colour) image recorded from the original seal.

Left: Two, scaled-up, 3D printed facsimiles of Sigill. Aram. V, made in the print rooms at Factum Arte, Madrid. Right: The two tiny facsimiles in the centre of the group are printed at actual size. Variations of enlarged facsimiles were produced, either uncoloured or with renders printed on their surface.

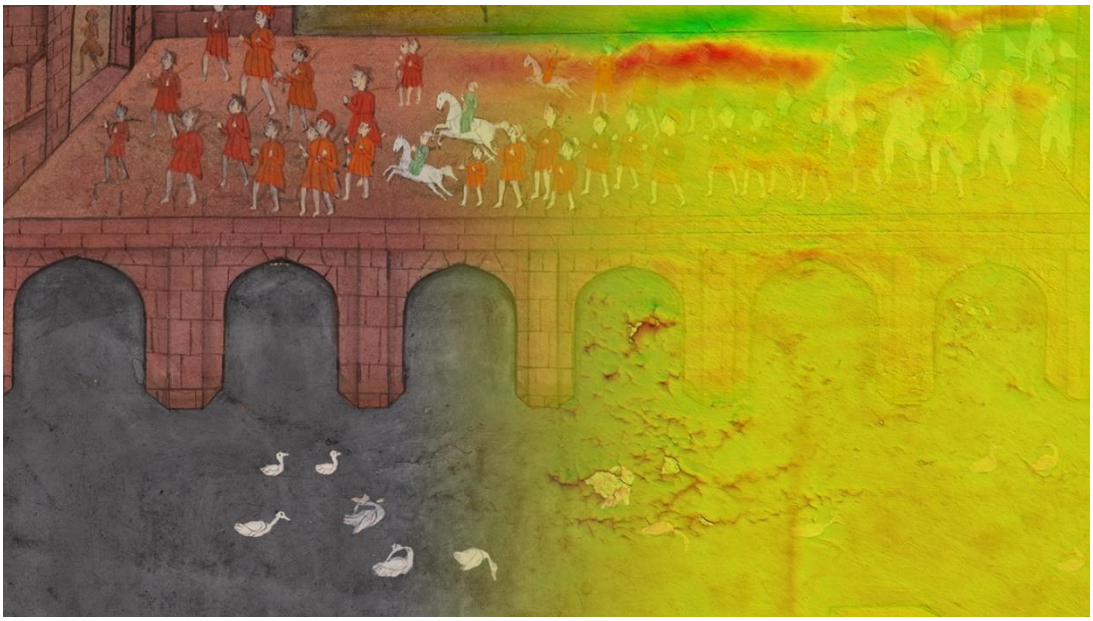
A far greater challenge would be to create a facsimile of the lost cylindrical seal which was used to make the impressions in the seven bullae. Though the fifth, seventh and eighth seals provide much of the design, some elements are clearly incomplete. A collated line drawing from Christopher J. Tuplin and John Ma's book, *Aršāma and his World: The Bodleian Letters in Context* reveals two important missing elements from the design. In the drawing, the horse to the left of the soldier holding a spear appears complete. Crucially so too does the inscription above the horse. With the assistance of Professor Tuplin, these additional details were explained. Another seal bearing a partial impression, made using the same cylinder is held in the collections of the Persepolis Fortification Archive in Chicago. A photograph of this seal was used by Eduardo Lopez from Factum Arte in order to incorporate the missing elements into the digital reconstruction.

The lost cylindrical seal, remade. The design from the collated recordings 3D printed onto flexible plastic before being glued to a cylindrical base. An impression in plasticine demonstrates that the facsimile is capable of creating incredibly similar designs to those found on the original bullae.

Prior to producing the facsimile, the 3D recording was inverted so that the embossed design would be capable of creating an impression similar to those from the original bullae. Though limited by the resolution of the 3D printer, the facsimile cylindrical seal is indeed a usable tool and capable of making impressions which look very similar to those which were ordered to be made by Prince Aršāma, two and a half thousand years ago.

The previous examples have demonstrated how faithful representations, either in the form of tangible 3D facsimiles or as on-screen, interactive 3D recordings can contribute to the preservation of an original. But conservators may also be able to use 3D recordings as an alternative, or in addition to traditional methods of condition reporting. Documenting changes to an original due to being handled, exhibited or prior to and following conservation treatment could be an important use-case for 3D renders. Conservation-specific elements such as flaking paint and insect damage are both clearly visible from the render and are also measurable. Virtually relighting these *condition maps* is clearly preferable to exposing an original to prolonged direct lighting. This is especially important in cases where the pigments used in the production of an original may be light sensitive. In addition, being able to share highly detailed recordings digitally could allow for remote consultation between conservators working in different institutions.

> *"3D renders offer great potential for conservators as a tool for interpreting and documenting the condition of items currently captured using conventional photography with raking light. With the ability to create composite images and to manipulate on-screen recordings altering the direction of light virtually, greater detail could potentially be revealed and recorded. Direct comparison against an original object would be key to interpreting the renders, distinguishing specific types of damage associated with an item's condition from other material characteristics. For example, damage to paint layers in manuscripts could be differentiated from differences in their depth or the relative depth of distortions in paper or parchment. Although certain materials or formats may pose difficulties, for example distorted paper and parchment or the flexed leaves in bound volumes, it may be possible to make direct and measurable comparisons of an item's condition clearly showing any changes. This would be particularly useful, for example before and after transport and display or longer-term storage and handling, saving time in the process of condition reporting objects."* Robert Minte ACR, Paper Conservator, Bodleian Libraries.

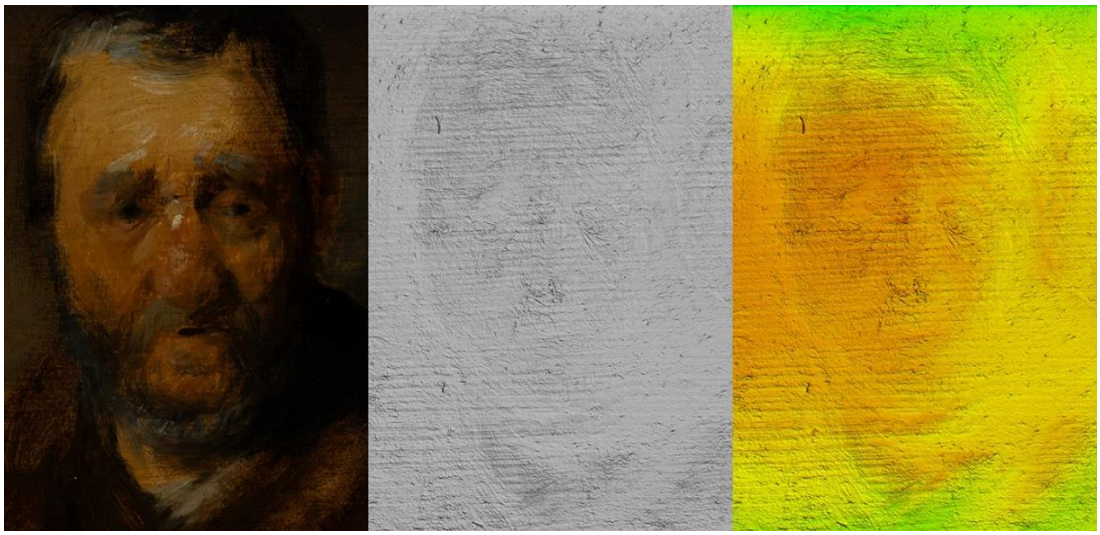


Left: an albedo recording of a 17th- 18th century Indian painting. Right: An example of how a heat map render, layered with a low-opacity albedo image can be used to record surface damage. 'Condition maps' could be an effective new method of condition reporting. MS. Douce Or. b.3.

The Factum Foundation have extensive experience in creating three-dimensional facsimiles of paintings from cultural heritage institutions around the world. During the last decade, a 3D scanner called the Lucida has been used to make these recordings. By projecting a laser line onto the original's surface, the scanner is able to capture the surface topography with incredible precision. A render of the surface is then processed from this data and conventional photography aligned to it so that the two are perfectly registered. For the recording of paintings, the Selene photometric stereo recording system provides several significant improvements over its predecessor. Both the depth map, which stores the 3D data, and a colour recording can be processed from the source images captured with the Selene; a far more efficient method than making two separate recordings which would need to be aligned. Crucially, data captured with the Selene is approximately four times the resolution of the recordings made with the Lucida and requires significantly less computational power to render.

A small wood panel painting believed to be the missing 'Old Man' by Rembrandt van Rijn, circa 1627-29. Courtesy of Agnews, London.

The portrait pictured above is believed to have been painted by Rembrandt van Rijn; a small wood panel painting, missing since 1935. It was brought to the Bodleian from Agnews Gallery, London, to be recorded with the photometric stereo system. The Selene has recorded the relief of the painting in incredible detail. The brushstrokes are particularly notable beneath the eyes where thick layers of paint have been applied. Horizontal markings visible from the render show the saw-marks made during the preparation of the wooden panel on which the portrait was painted. In addition, three tiny brush hairs, two of which had not previously been detected due to their small size and location within areas covered by dark paint have also been identified. This example shows how 3D recordings made with the Selene have the potential to support research and perhaps provide provenance to paintings. Recordings of this kind may also be used for the production of incredibly accurate 3D facsimiles, which could be exhibited in place of originals which are undergoing conservation treatment.



Three derivative images processed from data captured with the Selene. Left: an albedo image showing the colour of the original. Specular highlights are avoided due to the albedo being lit from multiple directions. Centre: a shaded render of the surface of the painting. Right: A heat map render using colour to represent height. Courtesy of Agnews, London.

> *"Technological developments like the Lucida 3D Scanner were conceived to demonstrate that paintings are not simply flat objects, so being able to capture, visualize, measure, and reproduce their relief characteristics is vital to understanding them to their fullest. The surface relief talks eloquently about the technique employed by the artist in creating the artworks (ie. through describing brushstrokes). But it also speaks about the historic trajectory of the painting, its conservation state, and the footprints and scars left by the passing of time – and the human interventions that attempted to reverse their effects.*
>
> *Now the Selene scanner is demonstrating that the page of a book is not a flat thing either, and much can be discovered out of describing its surface as a material reality, beyond the texts so images that can be seen at plain sight".* Carlos Bayod Lucini, Head of 3D Scanning, Factum Foundation

The recordings featured in this article are a small selection of many hundreds made during the first year of ARCHiOx. Both the Lucida and Selene 3D recording systems will remain at the Bodleian. Their continued use will undoubtably lead to further discoveries. Recordings of our most treasured and fragile originals will ensure their preservation, while supporting research.

Jorge Cano and his colleagues at the Factum Foundation will continue to develop the Selene with the aim of installing photometric stereo recording systems in other institutions. The Bodleian will assist with this development, testing each workflow iteration though making recordings of a wide range of the Library's originals. In this way, the collaboration between the Bodleian and the Factum Foundation will continue.

The collaboration between ARCHiOx and researchers, curators and conservators is of equal importance. Their suggestions regarding which originals may benefit from 3D capture, and how best to present the recordings have played a vital role in steering the project's course throughout its first year.

What has been proven through the recordings made with the Selene during 2022 is that photometric stereo imaging is every bit as effective at unlocking the mysteries of collections material as established heritage science imaging techniques such as hyperspectral and x-ray imaging.

Given the range of possibilities which the Selene recordings permit: measurement, virtual relighting, on-screen 3D navigation and futureproof data suitable for the production 3D facsimiles, photometric stereo is without doubt, a significant new addition to existing methods of cultural heritage imaging.

Text and images by John Barrett, February 2023

The incredible work of the **Factum Foundation** is documented on their website www.factumfoundation.org

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