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The X-Ray Micro-CT of a Full Parchment Codex to Recover Hidden Text: Morgan Library M.910, an Early Coptic *Acts of the Apostles* Manuscript

Paul C. Dilley, *University of Iowa*;
Christy Chapman, *University of Kentucky*;
C. Seth Parker, *University of Kentucky*;
W. Brent Seales, *University of Kentucky*

One of the oldest near-complete copies of the Acts of the Apostles is found in codex M.910, a damaged Coptic manuscript copied sometime in the fifth or the sixth century, now held by the Morgan Library and Museum in New York, where it has eluded scholarly eyes for decades due to its fragile state.[1] The Morgan Library and Museum (then known as the Pierpont Morgan Library and hereafter as the Morgan) purchased the manuscript in 1962, while in the midst of acquiring another

1 Leo Depuydt, who catalogued the Morgan's famously extensive collection of Coptic manuscripts, notes briefly: "It contains Acts in Sahidic and probably dates to the fifth or sixth century AD." *Catalogue of Coptic Manuscripts in the Pierpont Morgan Library* (Leuven: Peeters, 1993), LXXX. M.910 does have a trismegistos number (108698): https://www.trismegistos.org/text/108698.

Coptic Acts of the Apostles codex, the Codex Glazier.[2] Although Hans-Martin Schenke edited this text in the Middle Egyptian dialect of Coptic in the 1980s, M.910 still awaits publication. This will soon be possible, however, thanks to collaboration between a scholar of early Christianity and Coptic (Paul Dilley), a computer scientist with a research focus on the digital recovery of ancient texts (Brent Seales and his team at the University of Kentucky), and the head of conservation at the Morgan (Maria Fredericks).[3] These specialists convened at the Morgan from 11 to 18 December 2017 to image the damaged manuscript with a SkyScan micro–computed tomography (micro-CT) scanner, donated for use in this project by Micro Photonics, the U.S. distributor, and operated by Raj Manoharan.[4] A second round of imaging focusing on a smaller set of fragments and separated pages was carried out 18–22 November 2019 at Micro Photonics' headquarters in Allentown, using the SkyScan 1272 and 1273 scanners, operated by Seth Hogg. Ben Ache of Micro Photonics coordinated on both occasions. Work on processing the images, and reading the resulting text, has been ongoing.

This preliminary report will provide an overview of the manuscript and the imaging process, with a focus on the practical aspects of simultaneously addressing philological, conservation, and engineering challenges. To our knowledge, this work represents the first attempt to use X-ray imaging to read inaccessible writing on both sides of a surface (as opposed to scrolls with writing on one side), within a codex of substantial size.

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2 Morgan Library and Museum, "Acquired in Egypt by the Dutch dealer Joh. Möger of Soestdijk, The Netherlands, in the spring of 1962, and purchased by the Library in that year," available at https://www.themorgan.org/manuscript/214334 (M.910). For the Glazier codex, see Morgan Library and Museum, "Purchased in Dec. 1961 from H.P. Kraus, New York for William S. Glazier (1907–1962), New York; deposited in the Pierpont Morgan Library by the Trustees of the William S. Glazier in 1963," available at http://corsair.themorgan.org/vwebv/holdingsInfo?bibId=77061.

3 We would like to thank Maria Fredericks, Frank Trujillo, and other staff at the Morgan Library and Museum for making this work possible.

4 In addition to the generous support of Micro Photonics, the project was funded by an Arts and Humanities Initiative grant from the University of Iowa.

M.910 As an Early Coptic Witness to Acts of the Apostles

On-site examination at the Morgan has confirmed that M.910 indeed contains Acts of the Apostles in the Sahidic dialect. The book-block is made of extremely thin parchment leaves with much of the binding thread still intact. It is also accompanied by its original wooden covers. The back cover has been separated from the manuscript, rendering the last several pages visible, despite severe damage to them. The front cover is still attached, making it impossible to inspect the opening pages with the naked eye. However, the Morgan Library and Museum records include a set of fourteen black-and-white photos of several pages, apparently taken by the dealer before the sale, at the sections of the book-block that opened without prying. I have transcribed these pages, which will help to identify text in the processed 3D images. They also reveal that the codex leaves were numbered in the upper right corner; because of damage, only two were clearly legible: ⲓ̅ⲑ̅ (19, page contains passages from Acts 3) and ⲕ̅ⲧ̅ (23, page contains passages from Acts 4). The photographed pages are almost all from the first half of the manuscript, likely because they were less damaged. My inspection of the last page of the codex, the only one which is currently exposed, revealed Acts 27:24–28, with several fragments of additional pages after it. This strongly suggests that the codex contained all of Acts of the Apostles within its two covers, and nothing more. The manuscript's entry states that it contains 102 leaves. How this number was arrived at is uncertain, and the number will have to be verified through a careful consultation of the processed images.

Notes taken by the scholar Theodore Peterson after M.910 was acquired, which are now available online, offer some additional clues to the damaged codex's contents. He writes that its text of Acts "differs from the published texts only in a few individual spellings" and that "the recension of the text is the 'Alexandrian' one."[5] Under "published texts" should presumably be included the eclectic text of the Sahidic Acts of the Apostles, volume 6 in Horner's seven-volume critical edition of the Sahidic New Testament.[6] In

5 Morgan Library and Museum, https://www.themorgan.org/manuscript/214334.

6 George William Horner, *The Coptic Version of the New Testament in the Southern Dialect,* vol. 6: *Acts of the Apostles* (Oxford: Clarendon, 1922).

addition, two other early Coptic manuscripts of Acts have been published: London, British Library MS. Or. 7594, nearly complete, and in the Sahidic dialect; and the Glazier Codex (Morgan Library and Museum, MS G. 67), which contains a version in the Middle Egyptian/Oxyrhynchite dialect through chapter 15:3.[7] Peterson's assessment of the text of Acts was likely based on the fourteen black and white photographs, which is too small a sample to identify it securely with any one tradition. Whether or not it is "Alexandrian," the apparent similarity to already edited versions of the Coptic text will be useful as we begin in earnest the collaborative work of identifying further passages through processing of images. I have already identified one passage, Acts 10:4–6, from the middle of the manuscript, and we anticipate many other identifications in the coming year in this groundbreaking project.

Recent results using micro-CT to reveal written material provide a pathway for digitally restoring extremely damaged heritage objects like the M.910 manuscript.[8] Unlike with a traditional camera, a micro-CT scan allows the acquisition of a three-dimensional, or volumetric, data set that captures the structure of every page of the manuscript—and the ink on the page—without ever touching or turning the fragile folios. Yet, despite the promise it holds, digitization via X-ray computed tomography is not without its own constraints that present their own challenges.

Mounting

The first problem to be solved is the positioning of the manuscript in the scanner. For a book or codex with a binding, the safest orientation is horizontally resting on its face or back, as if placed on a table to open the cover. This orientation, however, is exactly the wrong one for micro-CT capture.

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7 E. A. Wallis Budge, *Coptic Biblical Texts in the Dialect of Upper Egypt* (London: British Museum, 1912); Hans-Martin Schenke, *Apostelgeschichte 1,1–15,3 im Mittelaegyptischen Dialekt des Koptischen (Codex Glazier)* (Berlin: Akademie Verlag, 1991).

8 W. Brent Seales, C. Seth Parker, Michael Segal, Emanuel Tov, Pnina Shor, and Yosef Porath, "From Damage to Discovery via Virtual Unwrapping: Reading the Scroll from En-Gedi," *Science Advances* 2, no. 9 (2016), https://doi.org/10.1126/sciadv.1601247.

Instead, a codex must be placed vertically on one of its four edges, while the X-ray beam is typically positioned so that it shines from left to right—that is, parallel to the floor and ceiling. To achieve this orientation, M.910 had to rest on its spine since any other vertical placement was impossible due to the thin, brittle edges of its pages. However, the codex's rare wood binding is itself quite fragile, necessitating some type of cushioning. In addition, to acquire the full 360-degree range of images necessary to construct a three-dimensional view, the object must be able to rotate as the micro-CT scan progresses, thus requiring some sort of protection from vibration and abrasion during movement.

Finally, to ensure that the X-rays pass evenly through an object, scanned material needs to be of relatively uniform shape—something like a solid sphere or cylinder. However, in the case of bound manuscripts like M.910 (and most damaged heritage objects, in fact), such uniformity does not occur. The large flat surface of a page is significantly wider than the total thickness of the manuscript. Without some sort of mitigation, X-rays projected through the thickness of the manuscript as it rotates will be significantly brighter than those that pass through the thinner, edge-on orientation, resulting in a disparity that can greatly affect the quality of the scan.

Therefore, the research team worked with the conservators of the Morgan to design a mount that would hold the manuscript in the scanner with its binding down, safely wedging the codex between two vertical uprights.[9] The resulting case (fig. 1) consisted of two half-cylinders made from 3D printed plastic that slid together and left a rectangular gap in the middle for manuscript placement.

This arrangement also created the solid cylindrical shape needed for even X-ray attenuation. In addition, the mount could be assembled while in a horizontal position, keeping the manuscript safely flat on its back during preparation (fig. 2).

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9 See Maria Fredericks, "Inside Story: Using X-ray Microtomography to See Hidden Features of a Manuscript Codex [blog post]," Morgan Library and Museum, available at https://www.themorgan.org/blog/inside-story-using-x-ray-microtomography-see-hidden-features-manuscript-codex.

FIGURE 1. Illustration of the cylindrical shape of the mount and its assembly process.

FIGURE 2. The M.910 manuscript is prepared for placement in the scanner. Foam and support boards ensure a firm but reasonable fit against the manuscript.

FIGURE 3. The manuscript encased, binding down, in the micro-CT machine. The black circular base remained in the scanner, allowing the manuscript case to be easily, gently, and securely installed using nylon set screws.

Nestling M.910 in the cradle in this way allowed the rotation in the beam to be safely repeated as necessary during the scan (fig. 3) and provided a stable mechanism for transporting the object from its storage location downstairs to the scanner each day.

Resolution

Another key limiting factor of tomography pertains to the target resolution of the final scan, as it determines to a significant degree what can be achieved downstream when processing the images. Measured by caliper, the pages of M.910 are approximately one hundred microns thick, which is very thin for parchment. This contraction in thickness—to perhaps half that normally found in modern parchment—is most likely due to the extremely desiccated disposition of the ancient parchment. Multiple sand particles confirm that it spent centuries in a dry location.

At a page thickness of one hundred microns, tomography would need to produce an image slice at approximately every thirty-three microns to achieve only three samples through the thickness of a page. However, with only three samples, it would be difficult to detect the difference between the parchment and the much thinner layers of ink that coat a page's recto and verso. As illustrated in figure 4, the larger the size of the voxel, which is a pixel in 3D, the less granular and detailed the data. In fifty- and thirty-three-micron scans, the ink signal will be commingled with that of the writing surface. At twelve microns, the ink layer is separable from the substrate, and at eight microns, the tomography can even capture the variation between ink on the very top surface of the parchment versus the small amount that has soaked into the material fibers.

Such variations are key to distinguishing recto from verso text and successfully applying our machine learning tool for ink identification. The team therefore aspired to achieve a resolution of ten microns, which would provide ten image slices throughout the thickness of every page, and sought a setup in terms of time and orientation that would lead to this result.

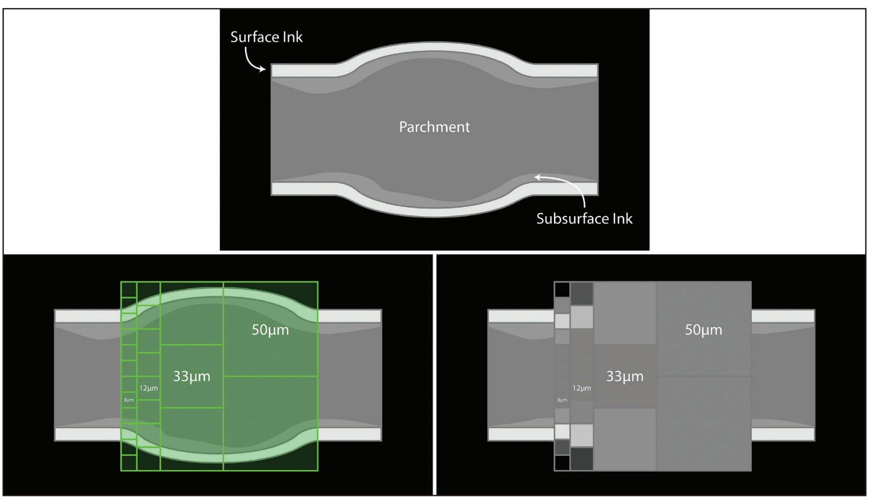

FIGURE 4. An illustration of the importance of resolution. The green squares (left) represent the voxel size and reveal how a large voxel is dominated by data about the substrate material, but smaller voxels capture much more granular and ink-informed data (right).

Because of the manuscript's fragility and the Morgan's reluctance to see M.910 travel, we arranged for two scanning sessions: a primary one at the Morgan in Manhattan, for which a micro-CT system was set up on-site to conduct the imaging of the entire manuscript; and a secondary one some months later for portions of the manuscript that were already separated from the overall codex and therefore able to travel safely.[10] This secondary scan also provided access to additional equipment as well as test data using different scan parameters, such as resolution and incident energy distributions.

Our preferred micro-CT system at the time was the SkyScan 2211 multiscale machine. However, its substantial weight, size, and, therefore, lack of ready portability made it unsuitable for site work at the Morgan. In its place, Micro Photonics contributed the use of a SkyScan 1173 for the week of beam time necessary to acquire the data. Given the working volume of the SkyScan 1173 and the dimensions of M.910 (12.5 cm × 14.5 cm × 5 cm), the best spatial resolution we could acquire with the entire manuscript in view of the X-ray beam was thirty-five microns. With geometric magnification it was possible to scan a central core section of the manuscript at a higher spatial resolution of sixteen microns (fig. 5), but doing so required us to sacrifice the ability to image the entirety of every page.

We opted to continue with both scanning protocols to compare them and test the limits of the post-processing pipeline given resolution constraints. While it was immediately possible to see ink traces in the data (fig. 6), the reduced resolution made those traces less prominent in the scan of the complete manuscript. At the same time, the large data sizes of the higher resolution scan rendered the on-site analysis of the images cumbersome and difficult to achieve in a timely manner.

The second scan session at Micro Photonics headquarters in Allentown, Pennsylvania, on 18–22 November 2019, led to the acquisition of micro-CT scans of several fragments as well as a detached six-page section of the manuscript. We mimicked the protocols from the on-site scans to have

10 Our work on site was chronicled in Nicholas Wade, "Scanning an Ancient Biblical Text That Humans Fear to Open," *New York Times,* 5 January 2018, https://www.nytimes.com/2018/01/05/science/biblical-codes-morgan-library.html.

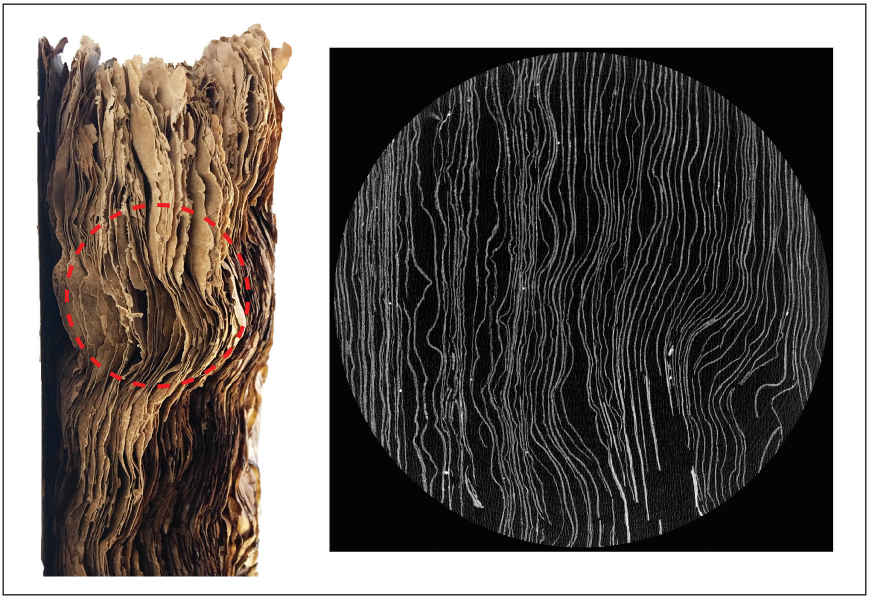

FIGURE 5. By zooming in on the core of the manuscript (left, image not to scale), we were able to achieve a sixteen-micron resolution scan (right). One can see the distorted and torn individual leaves of the manuscript in the slice image.

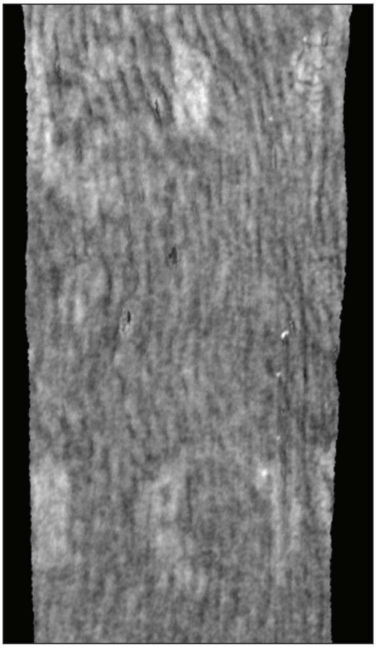

FIGURE 6. Faint traces of ink visible in the micro-CT scan of the manuscript core.

data comparable to M.910 in spatial resolution and beam intensity. However, we also acquired images with higher resolution and under varying intensities, or energy levels, of the X-ray beam to allow us to investigate questions regarding resolution limits and the contrast of the ink as a function of the scan protocol. We also planned to use the variety of data acquired together with high-quality reference photos provided by the Morgan to build a robust label set that could function as a reference for supervised learning algorithms. The hope is that these new tools will overcome the resolution limitations, enabling the teasing out of the recto/verso ink signals when the two would otherwise be hopelessly commingled.

While the equipment we used produced detailed and predictable data, it revealed again the need for tomographic equipment purpose-built specifically for heritage applications. Many of our concerns with mounting, handling, positioning, and discovering appropriate scan protocols (energies, scan times, desired spatial resolutions) could be mitigated using a system designed from the beginning to address heritage challenges. We hope to inspire this kind of future engineering in tomography-for-heritage applications in partnership with companies like Micro Photonics and Bruker Micro-CT.

Preliminary Data Analysis

After processing the tomographic data, it was possible to view the acquired 3D images of the manuscript with straightforward volume visualization tools that are used in all tomographic applications. We were immediately able to reveal the detailed internal structure of M.910's binding, down to the threads connecting the quires that represent the unique pattern of construction that M.910 exemplifies in the history and evolution of book technology (fig. 7). Even in the lower-resolution, thirty-five-micron scan, the structure of the manuscript as well as its composition of pages into quires and the sewn binding were immediately visible.[11]

11 See Fredericks, "Inside Story."

FIGURE 7. Micro-CT images illuminating the unique binding structure of the manuscript.

As for the writing, we discovered soon after the reconstruction of the tomographic data that at least two types of ink application appear within the manuscript. In some places, the ink is high contrast and appears quite clear to the naked eye. In other places, visible contrast is low to undetectable. These variations could be explained by the use of multiple ink recipes or by the deterioration of the iron gall ink, but these explanations deserve further study. We have discovered that there is significant textual information stored in the tomographic data that cannot be seen by the naked eye but can be extracted through more sophisticated computational methods. Photographs of the exposed pages can be taken and correlated with the micro-CT data, providing a roadmap to how that writing appears in X-ray.

Conclusion

Despite the aforementioned challenges, the acquisition of photographic and tomographic data of M.910 manuscript was a success, yielding images that clearly show ink signal and the binding structure, as well as providing the opportunity to render page-by-page views of all its internal, inaccessible leaves. All data was acquired without damage to the manuscript and without the need to turn a single page. The process led the team closer to a conservation protocol for tomographic scanning, including assessment, measurement, mounting solutions, scanning protocols, and evaluation of post-scan conditions of heritage objects. The research team is now poised to develop follow-on machine learning algorithms that will be used to tease out the writing, both recto and verso, from the data without the need to handle or reference the original material.