##DIGITAL CLASSICS ONLINE##

Illuminating the Herculaneum Papyri: Testing new imaging techniques on unrolled carbonised manuscript fragments

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Abstract: This article describes the results of advanced imaging pilot testing on unrolled Herculaneum Papyri undertaken in 2014 as part of a collaboration between the Universität zu Köln and the Biblioteca Nazionale di Napoli.[1] Building on results obtained by a Brigham Young University team in 1999–2002 using near infrared (NIR) photography, the aim was to test the potential for improving legibility and documentation of surface structures by combining the non-destructive techniques of NIR and Reflectance Transformation Imaging (RTI). The results show that, in addition to achieving super high-resolution images with enhanced contrast between the black ink and carbonised papyrus, NIR-RTI enables more accurate recording of surface morphology and enables the user to clarify the relationships between the ink constrate and the papyrus substrate. The article also identifies areas for improving image acquisition and usability.

1. Introduction

This article concerns advanced imaging undertaken in 2014 on unrolled Herculaneum Papyrus fragments in order to assess the potential of integrating near infrared (NIR) photography with Reflectance Transformation Imaging (RTI) for improved legibility and understanding of the scrolls' physical structure. In what follows, I briefly introduce the dataset and summarise previous imaging work and some of the persistent challenges that motivated the pilot testing. The imaging hardware, software, capture technique and processing methods are then described,

1 The work presented in this article could not have been undertaken without the expertise and support of numerous colleagues and institutions. I am grateful to Jürgen Hammerstaedt (Universität zu Köln) for initiating this pilot project and to Robert Daniel (Universität zu Köln) for his support, as well as my colleagues at the Cologne Center for eHumanities. For the privilege to work on these precious documents and for their generous hospitality, I wish to express my gratitude to Mauro Giancaspro, the Director of the Biblioteca Nazionale di Napoli, 'Naples', Italy, and to Sofia Maresca, Director of the Officina dei Papiri Ercolanesi, and her staff. My thanks to Il Centro Internazionale per lo Studio dei Papiri Ercolanesi (CISPE) for their support, as well as Gianluca Del Mastro (Università di Napoli "Federico II") whose comments improved a draft of this article. I am also grateful to Richard Janko (University of Michigan) and Roger Macfarlane (Brigham Young University) for further comments and corrections. Thanks are also due to CISPE Fellow Sarah Hendriks and University of Michigan/CISPE Fellow Michael McOsker. Test 1 was undertaken with equipment lent by Excellence Cluster TOPOI, Freie Universität Berlin. For valuable advice on integrating NIR photography with the RTI capture procedure and on illumination sources, my thanks are due to Eleni Kotoula. For additional equipment, I thank Melissa Terras and Sarah Davenport (UCL Centre for Digital Humanities), and Stuart Laidlaw (UCL Institute of Archaeology). My thanks also go to Antonino Cosentino, Todd Hanneken, Marlin Lum, Lindsay MacDonald, Mark Mudge, Carla Schroer, and Keats Webb for valuable technical discussions, imaging advice and feedback on results, as well as to Tom Malzbender for discussions on the feasibility of automating RTI stitching. Parts of this article were presented in 2014 at the CISPE meeting in Naples (11–12 September 2014), and a meeting of The Friends of Herculaneum Society in Oxford (18 October 2014). Portions of this article were also presented at a Digital Classicist Berlin Seminar (3 February 2015) and I am grateful to Matteo Romanello, Felix F. Schäfer, Undine Lieberwirth, Francesco Mambrini, and Martina Trognitz, as well as Isabell Uta and Michaela Rücker for the opportunity to publish it here.

followed by presentation and assessment of selected results. Proposals for developing the imaging technique and user tools will be offered, as well as observations on integrating new imaging techniques into scholarly workflows. At this juncture, I should note that I come to this work not as a Herculaneum papyrologist nor as a formally trained imaging scientist, but as an Egyptologist whose research revolves around archaeological approaches to ancient script[2] with the aid of advanced digital imaging technologies. For several years now I have been working with dome-based and Highlight RTI techniques in museum and field contexts,[3] but it is thanks to this pilot project and the support of numerous colleagues that I have had the tremendous opportunity to delve into the world of the Herculaneum papyri and spectral imaging.

2. The Herculaneum Papyri and Previous Imaging

The survival of Herculaneum papyri is a direct result of a catastrophic eruption of Mount Vesuvius in 79 CE, which buried the coastal city of Herculaneum and neighbouring Pompeii. Pyroclastic flows of superheated gas, steam and mud overwhelmed these cities, causing great destruction and loss of life. At the same time, the resultant rapid rise in temperature to 300–320 degrees Celsius acted to carbonise and preserve various organic materials, including a portion of a large library of papyrus scrolls.[4] The site of Herculaneum lay buried until the mid-1700s when antiquarian activity led to the discovery of some 1000 charred scrolls in the so-called ‘*Villa dei Papiri*’. An unknown number were destroyed before the identity of these crumpled, blackened cylindrical objects was recognised, with many more being partially or completely destroyed during attempts to unroll and read them. Certain documentation methods, such as copying the exposed inscribed surface and then scraping it away to reveal the layer underneath, resulted in yet further loss.

Of those ‘successfully’ opened and sufficiently legible, the majority contain Greek writings including treatises from the Epicurean philosopher Philodemus of Gadara, while a smaller number (c.80) preserve Latin poetry and prose. The Herculaneum papyri are thought to be part of an ancient private library that may have belonged to Lucius Calpurnius Piso Caesoninus, a Roman politician and father-in-law of Julius Caesar.[5] Hundreds of unrolled fragments and a number of rolled scrolls are now stored in the Biblioteca Nazionale di Napoli, the former consisting of about 6000 fragments mounted on numerous trays or “*cornici*”, with between 2–30 fragments per *cornice*. The papyrus fragments I worked on were mounted on animal gut, in turn, glued to card (*cartoncino*) affixed with thumbtacks to a thin wooden board measuring about 50cm × 30cm and stored in a metal tray with a glass lid (Figure 1). The wooden board mount could be removed from the metal tray for photography, but further dismounting was not possible.

2 E.g. Piquette (forthcoming); Piquette (2008); Piquette and Whitehouse (2013).

3 E.g. Earl et al. (2011); and Piquette (2016), respectively.

4 Janko (2002), 25.

5 Gigante and Obbink (2002), 49.

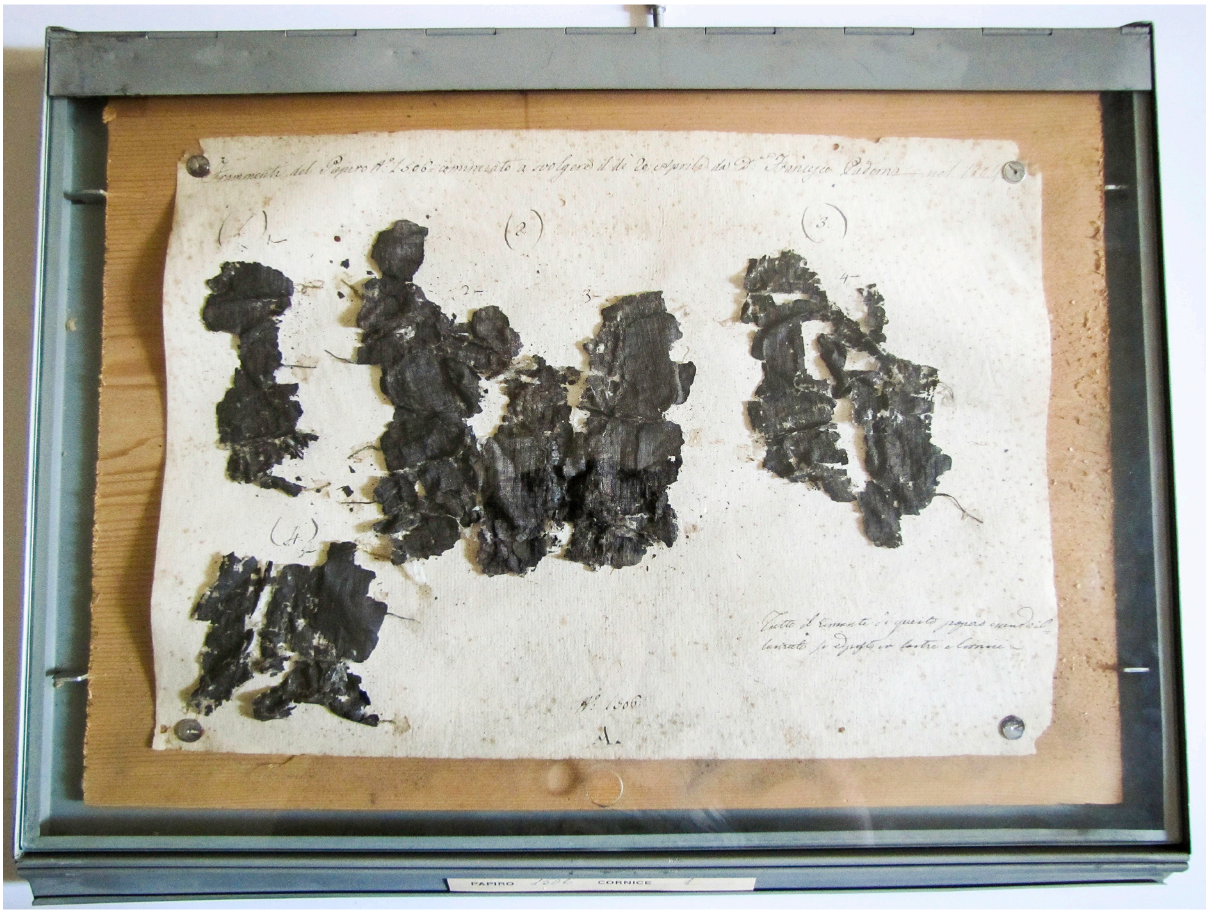

Figure 1: PHerc. 1506, Cornice 01 in storage box (Kathryn E. Piquette, courtesy Biblioteca Nazionale di Napoli).

The carbonised papyri with their black ink writings are notoriously difficult to read due in great part to their crumpled shape. In contrast to the usually planar surfaces of parchment and paper,[6] the shape of papyrus pith is inherently uneven at the micro-level, and even more so for the Herculaneum Papyri, which are uniquely complex in their meso- and macro-geometry (Figure 2). During pyrolysis – the process of carbonisation – water present in the papyrus substrate evaporates, causing buckling, twisting and shrinkage (estimated to be up to 30% of original scroll bulk).[7] Moreover, these effects are not uniform across a given scroll or the 'corpus'. Found in different locations within the villa, the scrolls would have been susceptible to different environmental conditions, as would sections of papyrus within the scroll itself, depending on whether closer to the inside or outside and depending on the presence of an umbilicus – a central baton around which the papyrus was wound. The saturation of the black colour of different fragments from the same or different scrolls therefore varies, and contrasts to different degrees with the ink. Likewise, the types of pigment, binder, or drying agent used in the ink and the techniques of its application will influence how it now contrasts with the papyrus substrate under visible light or other wavelengths.[8]

6 But cf. Pal et al. (2013).

7 Janko (2002), 30.

8 Tack et al. (2016).

Figure 2: PHerc. 78, Cornice 08 detail showing complex shape of papyrus (Sarah Hendriks, courtesy Biblioteca Nazionale di Napoli).

A variety of methods to increase contrast between the papyrus substrate and ink constrate have been attempted over the centuries. Recent efforts have been directed toward developing a non-destructive means of accessing the interior of scrolls that are still rolled and these have achieved remarkable results. X-ray computed tomography has proved successful for discerning the layers (and umbilicus) within the roll[9] while enhanced X-ray phase contrast tomography is bringing us closer to recording the ink as it sits on the papyrus within a scroll.[10] Otherwise, efforts have focussed on the unrolled fragments in Naples and it is on this material that our pilot testing was undertaken. The particular work that informs our own began over 15 years ago, as part of a two-phase spectral imaging project undertaken by a team from Brigham Young University (BYU). Commencing with tests in the autumn of 1999, the BYU team, supervised by Steve Booras, proceeded for over a year and a half to capture more than 30,000 photographs[11] of 1600 unrolled fragmentary papyrus scrolls.[12]
The equipment for the photography included a Kodak MegaPlus digital camera with standard Nikon 50mm and 100mm macro lenses, and produced images with a 300–600 pixels per inch (ppi) resolution. A motorised filter wheel with eight narrow bandpass filters was used. Illumination was applied using a German-made Dedo variable power lighting system that

9 Seals et al. (2011).

10 Mocella et al. (2015); Seales et al. (2016).

11 Information about the papyri can be searched here, although access to digital images is currently restricted: http://guides.lib.byu.edu/c.php?g=216482&p=1429231.

12 Booras and Seely (1999); Chabries et al. (2003), 368–371.

ensured the ambient temperature around the papyrus did not exceed 85° F.[13] Booras and Chabries report that attempts to increase contrast through near infrared radiation resulted in different responses from different carbonised papyri[14] but for most Herculaneum papyri, the optimal contrast response to NIR was between 850–1000 nanometres (nm).[15]
The clarity of the NIR images exceeded all expectations and launched a major leap forward in Herculaneum Papyri research, occupying papyrologists for well over a decade with enhanced and newly visible written content. Despite the major contribution of these visualisations, as with any new technique or evidence, new questions and issues arise. Certain technical drawbacks have been noted in publication[16] and also flagged up during my own discussions with Herculaneum papyrologists:

1. NIR photographs appear quite flat
2. Focus too soft in some areas
3. Fixed light position results in:
    a. Incomplete documentation of surface reflectance properties
    b. Difficulty discerning papyrus layers (*sottoposti* and *sovrapposti*)
    c. Difficulty discerning black ink from black colour of holes in papyrus
    d. Surface details obscured by self-shadowing
4. Overhead perspective and undulating surface results in distortion of letter shape
5. Some registration problems
6. Absence of scale bars

While gains in contrast and image resolution have vastly expanded access to the written content, conventional digital photography unavoidably produces fixed-light visualisations regardless of the light wavelength applied. Several of the shortcomings listed above are the direct result of this fixed relationship between the light source and complex geometry of the surface (3a–d), as well as the fixed angle between the camera and subject (3a, 4). Other issues relate to hardware, and imaging decisions or possible oversights (1, 5, 6).
Advances in hardware, software, capture technique and image processing, especially over the past decade, are now able to provide solutions to these issues. The computational photographic technique, Reflectance Transformation Imaging (below), has proven extremely helpful in addressing similar visualisation problems for, *inter alia*, writing on metal tablets from the Classical world, e.g. thin sheets of lead or other metals inscribed with a stylus, rolled or folded and ritually deposited.[17] Upon rediscovery, they are often unrolled for reading, their corroded and undulating surfaces presenting significant reading and recording challenges.[18] In late 2013, I had begun work applying RTI to lead tablets from the ancient Near East inscribed with Greek magical texts for the *Magica Levantina* project based at Universität zu Köln and led by Robert Daniel. During review of preliminary RTI results with colleagues, Herculaneum papyrologist Jürgen Hammerstaedt suggested the technique be trialled on the Herculaneum Papyri fragments in Naples with the aim of assessing whether the spectral imaging method employed by Brigham Young University could be fruitfully augmented to address some of the shortcomings described above.

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13 Booras and Chabries (2001), 3.

14 The reasons for this, no doubt contingent upon the variable micro and macro conditions of pyrolysis (above), have yet to be fully explored and present a promising area for spectral research.

15 Booras and Chabries (2001), 3; cf. Janko (2002), 28.

16 Macfarlane et al. (2007); Janko (2002), 29–30.

17 E.g. Gager (1992).

18 E.g. Piquette et al. (2011).

With the kind cooperation of the Biblioteca Nazionale di Napoli, two phases of pilot testing were planned and undertaken in February[19] and June 2014. The aim of Test 1 was to assess generally the effectiveness of Reflectance Transformation Imaging (RTI) for better capturing papyrus surface shape. Depending on the outcome, Test 2 would then combine the Highlight RTI capture technique with NIR photography for full comparison with the previous NIR photography.

3. Test 1: Visible Highlight Reflectance Transformation Imaging

For Test 1 undertaken on 6–7 February 2014, I used the manual highlight procedure for applying RTI. RTI is a method of structured light photography where a series of exposures are made, each with illumination applied from a different location and angle in a hemispherical configuration. This can be accomplished with a lighting dome[20] or illumination arch,[21] but for our purposes Highlight RTI (H-RTI)[22] presented a relatively affordable option with greater flexibility and portability for low-impact use in a library context.

H-RTI requires a tripod-mounted camera set up in a stable environment on a solid surface. Stability between both the camera and the subject is essential so that the shots register precisely, pixel on pixel. Only the light source moves. As set out in *Reflectance Transformation Imaging: Guide to highlight image capture* v2.0,[23] the photographer moves the flash around the subject, iteratively applying a full hemisphere of illumination. Systematic application of the light is aided with the use of a string for measuring distance and ensuring the centre of the light is aligned with the centre of the subject. The placement of one, or preferably two, reflective spheres in shot enables the position of the light source to be calculated for each exposure during processing. The shots are fitted together using the Polynomial Texture Mapping (PTM)[24] or the Hemispherical Harmonics (HSH)[25] mathematical algorithms. The resultant image file can be viewed in an RTI viewer, allowing the user to virtually relight the surface and apply enhancements to disclose features of potential significance that are not apparent during first-hand inspection or in conventional fixed-light photographs.

The H-RTI imaging setup for Test 1 was composed of Canon EOS 5D Mark III digital SLR (22.3MP) with a Canon EF 100mm f/2.8L IS USM Macro lens (with a B&W UV filter for lens protection). The illumination source was a Canon Speedlite 600EX-RT flashgun[26] controlled and synced with the shutter using a Canon-compatible Calumet Pro Series 4 Channel Wireless Trigger Kit (including transmitter and receiver) and an extra receiver to allow single operator functionality. The camera was mounted on Gitzo carbon fibre tripod on a Gitzo ball head on a geared column. The camera was positioned vertically on the reverse end of the column on a bottom plate, facing down to bring the camera close to the papyrus. This is also safer

19 Test 1 was undertaken with Highlight RTI system I built during a Marie Curie COFUND fellowship at the Dahlem Research School, Freie Universität Berlin, in cooperation with Excellence Cluster TOPOI.

20 E.g. Earl et al. (2011).

21 E.g. Webb and Wachowiak (2011).

22 Mudge et al. (2010); (2006).

23 Cultural Heritage Imaging (2010).

24 See Malzbender et al. (2001).

25 Gautron et al. (2004).

26 As a typical xenon flashtube, this has a fairly linear output in the range of visible light (400nm–700nm), but also has a powerful output in the near infrared region above 800nm. Dyer et al. (2013), 45, figs. 2–3.

for the fragile subject since the centre of gravity is between the tripod legs and reduces the likelihood of the tripod tipping under the weight of the macro lens – as compared with the camera mounted on the centre column oriented at 90°, although tripod weights aid stability and are advisable for all setups. This setup was installed on two large desks (Figure 3). Ideally a single surface should be used but vibration tests confirmed stability of the floor and overall setup. The camera was tethered to a laptop on a separate surface to ensuring that hard drive or fan spin did not compromise stability.

Figure 3: Test 1 workspace comprised of two large desks pushed together in upper room of library with stable floor. Mariacristina Fimiani, CISPE collaborator, looks on (Kathryn E. Piquette).

A selection of fragments exemplifying the issues described above was prepared by Gianluca Del Mastro and a subset were imaged (Table 1). Based on conversations with potential users regarding comfortable onscreen viewing of written characters measuring approximately 3mm–4mm at up to 100% magnification, a preference for resolution was established at 200 pixels per centimetre (ppc).[27] After taking account of the average width of a column of text and need to fit in a scale and two RTI spheres in shot, in most cases a 10cm–12cm area of papyrus was imaged at 100ppc–130ppc. Many fragments included in the test were larger than 10cm–12cm, necessitating consultation of two separate RTI files to view a single column of text (devising capture procedures that enable the stitching of RTI datasets remains an area for further work[28]).

27 Cf. Twycross (2008), 27–29.

28 Lindsay MacDonald (2015), 104–105 has developed a method for manual stitching data from two different RTI capture sequences post capture.

Test 1: Visible H-RTI
PHerc. 395, Cornice 04, Pezzo 01, right
PHerc. 862, Cornice 01, Pezzo 01, right
PHerc. 862, Cornice 01, Pezzo 02, right
PHerc. 1485, Cornice 10, Pezzo 01, lower left
PHerc. 1506, Cornice 32, Pezzo 01, lower left
PJoannowsky, Cornice 03, left

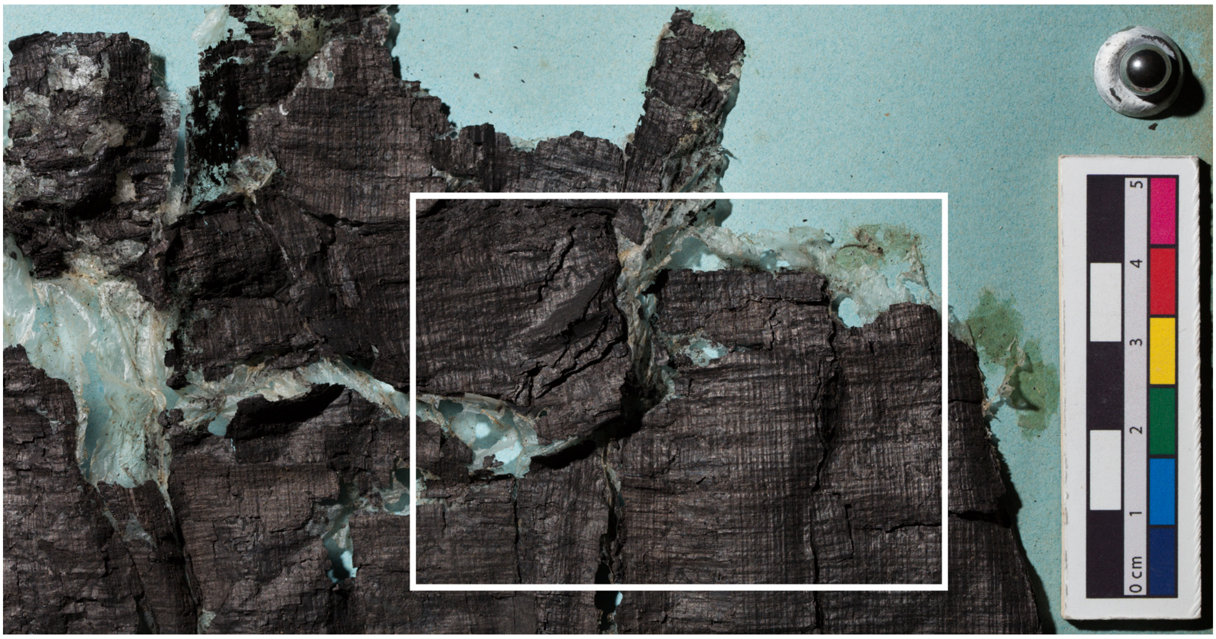
Table 1: Herculaneum papyri imaged for Test 1 using visible H-RTI.

Capture entailed taking about 48 images as well as a shot with the same camera settings of the X-Rite ColorChecker Passport for controlling colour, white balance and exposure. Cultural Heritage Imaging (hereafter CHI)[29] processing guidelines were followed. Adobe Lightroom 5 was used for pre-processing, including white balance and exposure adjustment and conversion of the RAW files to DNGs (with RAW embedded) and JPG. The latter were used with RTIBuilder 2.0.2[30] for processing and fitting into RTI user files. Both PTM and HSH formats were produced. The latter provided the best visualisation given that it calculates the surface normals more accurately and deals with self-shadowing more successfully than the PTM algorithm.[31] In the RTI viewer, the settings that produced the best visualisations were the specular enhancement rendering mode and the normals visualisation (see examples below).
The results demonstrated the success of the H-RTI technique, especially when processed with the HSH algorithm (Figure 4). However, the problem of contrast between the black ink and blackened papyrus remained largely unaddressed, necessitating a second test involving the integration of an NIR light source in the H-RTI capture procedure.

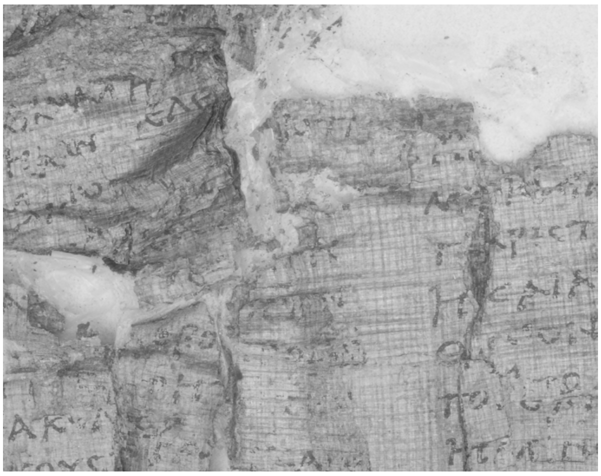
29 Cultural Heritage Imaging (2011).

30 Barbosa (2011).

31 Happa et al. (2010), 161–162.



a.



b.

c.

Figure 4: PHerc. 862, Cornice 01, Pezzo 02, detail of right side. a. As shot for the visible H-RTI Test 1. b. Detail of BYU spectral image (righam Young University, courtesy Biblioteca Nazionale di Napoli). c. Detail of RTI image (HSH), with the Specular Enhancement rendering mode applied (a. and c. Kathryn E. Piquette, courtesy Biblioteca Nazionale di Napoli).

4. Test 2: Near Infrared Highlight Reflectance Tranformation Imaging

Test 2 took place between 11–19 June 2014, the aim of which was to combine the Highlight RTI capture technique with near infrared photography and compare the results with the previous BYU NIR photography. With a modest project budget and extra-institutional collaboration, I was able to assemble an NIR H-RTI setup. The hardware used for Test 2 was composed of a UV-VIS-NIR modified[32] Nikon D800 digital SLR (36MP) with a CoastalOpt UV-VIS-NIR

32 Modification performed by Foto Gregor in Cologne, Germany.

APO, 60mm Macro lens with F74-F-45 F-mount,[33] and using a IR 950nm Delamax longpass/lowpass optical filter[34] (allows near infrared light with a wavelength greater than 950nm to pass but excludes shorter wavelengths). A near infrared BW® 48 LED Illuminator[35] with custom-made aluminium foil light throw provided a continuous light source (Figure 5). The camera was mounted on a Manfrotto carbon fibre tripod on a Gitzo ball head with the column reversed so the camera faced downward (Figure 6). Table 2 lists the fragments imaged during Test 2.

Figure 5: Near infrared BW® 48 LED Iluminator (30° beam spread) employed for Test 2 with customised light throw attached.

Figure 6: The author with the NIR H-RTI setup in the Biblioteca Nazionale di Napoli (Michael McOsker).

33 For equipment support, thanks are due to the UCL Centre for Digital Humanities, Multi-Modal Digitisation Suite, and Stuart Laidlaw of the UCL Institute of Archaeology.

34 With 58 > 52 adaptor ring.

35 This item was purchased on Amazon.co.uk and while the details did not state the wavelength of emission, very similar models elsewhere were stated as outputting at 850nm. It was not possible to confirm this with interferometric testing.

Test 2: Near Infrared H-RTI
PHerc. 862, Cornice 01, Pezzo 01, right
PHerc. 862, Cornice 01, Pezzo 01, upper right
PHerc. 862, Cornice 01, Pezzo 01, lower right
PHerc. 994, Cornice 09, Column 22, upper
PHerc. 994, Cornice 09, Column 22, lower
PHerc. 994, Cornice 09, Column 23, upper
PHerc. 994, Cornice 09, Column 23, lower
PHerc. 994, Cornice 09, right piece, upper left
PHerc. 994, Cornice 09, right piece, upper right
PHerc. 994, Cornice 09, right piece, lower left
PHerc. 994, Cornice 09, right piece, lower right
PHerc. 1506, Cornice 01, Pezzo 01
PHerc. 1506, Cornice 01, Pezzo 04
PHerc. 1506, Cornice 01, Pezzo 02, left
PHerc. 1506, Cornice 01, Pezzo 02, right
PHerc. 1506, Cornice 01, Pezzo 01
PHerc. 1506, Cornice 01, Pezzo 03
PHerc. 1506, Cornice 02, Pezzo 05, left
PHerc. 1506, Cornice 02, Pezzo 05, middle
PHerc. 1506, Cornice 02, Pezzo 05, right
PHerc. 1533, Cornice 01, Pezzo 05
PHerc. 1533, Cornice 01, Pezzo 04
PHerc. 1533, Cornice 01, Pezzo 01
PHerc. 1533, Cornice 01, Pezzo 02
PHerc. 1533, Cornice 01, Pezzo 03

Table 2: Herculaneum papyri imaged for Test 2 using NIR H-RTI.

As with any technological innovation, a period of familiarisation and problem solving is par for the course and is subject to a particular budgetary and scheduling framework. A literature survey in preparation for the work revealed only a small number of online resources and journal publications reporting on the integration of IR with RTI.[36] Eleni Kotoula kindly shared aspects of her doctoral research including NIR H-RTI work on the Derveni papyrus. Her advice was immensely valuable for planning this second phase, along with guidance from several other colleagues. Whereas Kotoula[37] was able to employ transmitted NIR for her work on the glazed, card-mounted Derveni papyrus (as well as reflected NIR), the mounting of the Herculaneum fragments precludes transmission.

Incandescent lamps output IR but produce heat that may be damaging to archaeological materials, in contrast to NIR LEDs which do not accelerate thermal degradation.[38] The choice of an LED illumination source followed Kotoula's lead, although the particular LED unit I was able to obtain within the available time and budget was quite low in power with a narrow beam spread. These combined to create several challenges. The beam spread limited the size

36 Caine et al. (2011); Gabov (2010); Kotoula (2014).

37 Kotoula (2013).

38 Kotoula (2014).

of the area that could be evenly illuminated while near invisibility made it difficult to ensure accurate light direction.[39] An improvised light throw of aluminium foil improved coverage slightly (Figure 5), but some vignetting did occur. Fortunately, the sections to be imaged were 10cm–12cm in length or width (for resolution reasons noted above) and even illumination could just about be achieved when holding the light at the recommended distance of 3×–4× the diagonal measurement of the target surface.[40] Although the ideal ISO setting for RTI capture is 100, the low power of the illumination source required an increase in both ISO and exposure time. ISO 400 produced a noticeable amount of visual noise, but a usable result was obtained with ISO 200 and an exposure time of 1/4s. It was also possible during processing and viewing, as described below, to enhance image brightness. Low light strength also necessitated setting focus with a more powerful light source. A modelling lamp on a mini studio strobe was placed at a distance from the camera setup and turned on only briefly to set focus (Figure 6, left).[41] Compared with visible RTI acquisition using a speedlight or similar source, NIR capture was somewhat slow and cumbersome. The exposure time required holding the light source steady while maintaining somewhat contorted positions as I progressed around the setup. Efficiency was also impacted by the LED illuminator being powered from the mains, necessitating careful manoeuvring with a trailing power lead.[42] A short safety lanyard attached to the unit and my wrist ensured that if I dropped it, the illuminator would not come into contact with the papyrus. With more time and funds, and as technology improves, a battery-powered IR LED source with higher and adjustable power and wider beam spread will provide more accurate illumination, increased capture speed, and reduce vibration risks.

The reader may rightly ask why a speedlight flash unit was not used. Time constraints in gaining access to funds for purchasing hardware, complex logistics involved in camera modification and its reunification with the rest of the new system left limited time for familiarisation and testing of the full setup before deployment on-site in Naples. Previous flawless performance of Calumet wireless triggers with the Canon setup used for Test 1 led to misplaced (in retrospect) confidence in a repeat performance with the new Nikon configuration with Calumet wireless triggers (Nikon brand triggers could not be afforded within the project budget). It was discovered upon arrival in Naples that the Calumet triggers sold as compatible with the then new Nikon D800 were, in fact, incompatible and syncing the shutter and flash proved impossible. After Test 2 was completed, an afternoon of troubleshooting back in London with Calumet and Nikon specialists resulted in a workaround being devised. By using the Nikon Commander Mode and pop-up flash for IR communication with the Speedlight, correct sync was achieved. So that the pop-up IR flash does not, however, interfere with the RTI IR light source, a Nikon FXA10358 IR Panel can be used to cover the built-in flash and prevent its influence on exposure. It is worth noting that, as was discovered during subsequent use, if this panel sits flat against the pop-up flash, it may interfere with Speedlight communication when in certain positions, but if the panel is tipped away slightly, communication is maintained as the Speedlight is moved around the setup during capture. As tests demonstrated, the small amount of leakage from the pop-up IR flash does not influence the exposure.

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39 Such NIR LED units often have a built-in light sensor, and in order to ensure constant, full power illumination, the sensor must be covered. Removing the protective glass cover, covering the sensor with Blu-Tack, and replacing the unit cover achieved this.

40 CHI (2013), 18.

41 Because most of the energy emitted by such tungsten or tungsten-halogen bulbs is in the NIR range and produces heat that may degrade papyri (Leach and Tait (2001), 239–240), use of the modelling lamp was kept to a minimum.

42 Use of a battery pack is advisable to avoid trailing cables that might present tripping hazards or bump the setup. However, I was able to keep the lead clear by attaching and trailing it up my arm and over my shoulder with Velcro strips.

Returning to the workflow of Test 2, in order to record the position of the light in each exposure in the series, two reflective ball bearings were placed in shot. These were machined down beforehand at UCL but ensuring their original diameter was preserved. This truncation had the benefit of reducing sphere height and thus minimising the depth of the effective focus range required to accommodate the upper third of the spheres along with the papyrus surface. This is important as an aperture smaller than f/11 should be avoided as this results in a loss of sharpness.[43] The spheres were carefully placed on the *cartoncino* or, to avoid surface contact, affixed to chopsticks suspended above the papyrus at the edge of the framed view, together with a scale. At the end of each capture sequence with camera settings unchanged, an X-Rite ColorChecker Passport was imaged with illumination from 65°.

As above, CHI processing guidelines[44] were followed, although additional steps were required for the NIR data. Because the image sensor of the modified camera is colour, the image will have a reddish cast. The images were therefore converted to greyscale before conversion to DNG and JPG. As mentioned above, the exposure achieved with this particular LED light source was usable but suboptimal. In order to try to brighten up the image while avoiding degradation, I conducted a series of tests where by the JPGs required for creating RTI image files were exported with incrementally higher exposure adjustment (i.e. +0.7, +1.0, +1.5, +2.0, +2.5, +3.0), followed by processing with RTIBuilder. Comparison of surface normals visualisations at 200% magnification in the RTI viewer revealed no visible[45] degradation for adjustments between +0.7 and +2.0, but did begin to appear around +2.5. I therefore processed with a +2.0 exposure adjustment. It is important to note that in all cases when the capture series was fitted using the Polynomial Texture Mapping (PTM) algorithm,[46] the results were too dark to be usable. However, excellent visualisations were produced when the data was processed with the Hemispherical Harmonics (HSH) algorithm and when viewed in the RTI viewer using the Specular Enhancement rending mode with the following settings: Diffuse color = 0; Specularity = 100; Highlight Size = 1.

5. Assessment of Results

Throughout the pilot testing and especially following the completion of Test 2, user files were reviewed with Herculaneum papyrologists, including Jürgen Hammerstaedt, Gianluca Del Mastro and Richard Janko.[47] Their assessment was that the integration of NIR photography with the H-RTI capture technique presented a marked improvement over previous imaging methods and provided a vital complement to first-hand inspection using microscopes and raking light. However, barriers to efficient use include the large file size and need to consult multiple files for a single papyrus document due to the present inability of RTI captures to be stitched. For exposed layers of unrolled Herculaneum papyri, this technique with the ability to virtually relight the surface addresses most of the aforementioned shortcomings of fixed-light photographs.

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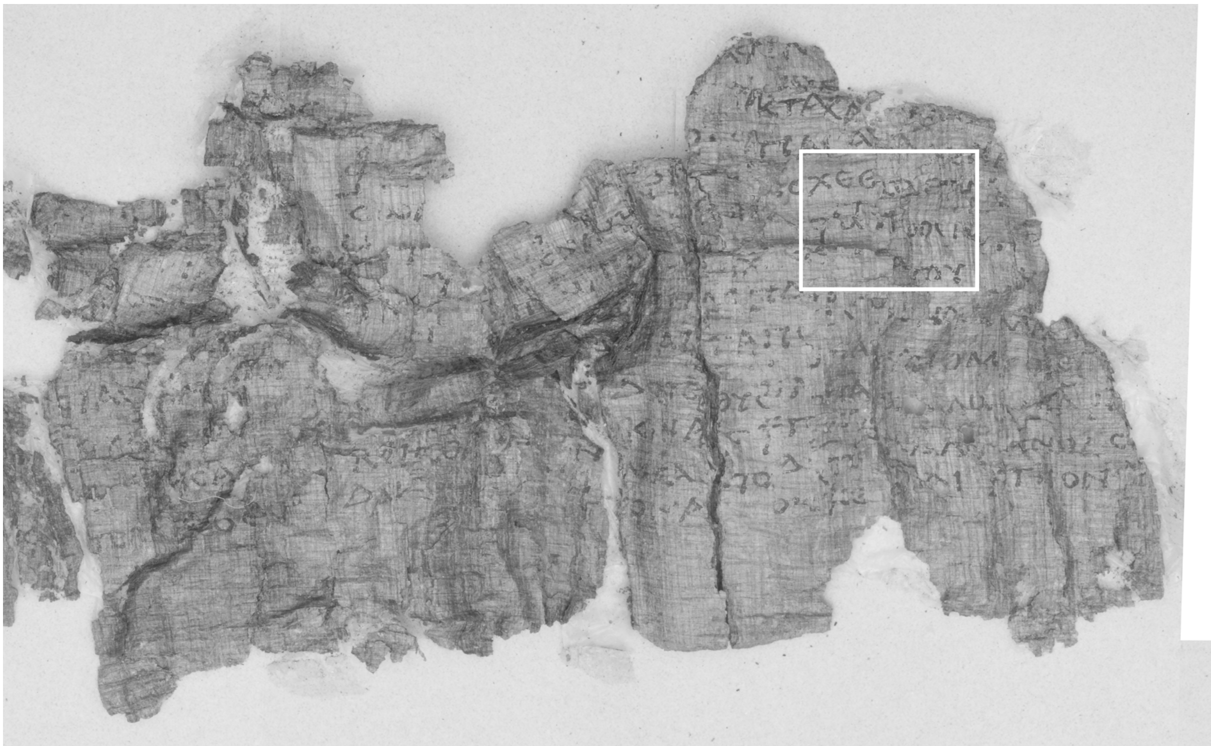
43 CHI (2013), 26.

44 Cultural Heritage Imaging (2011).

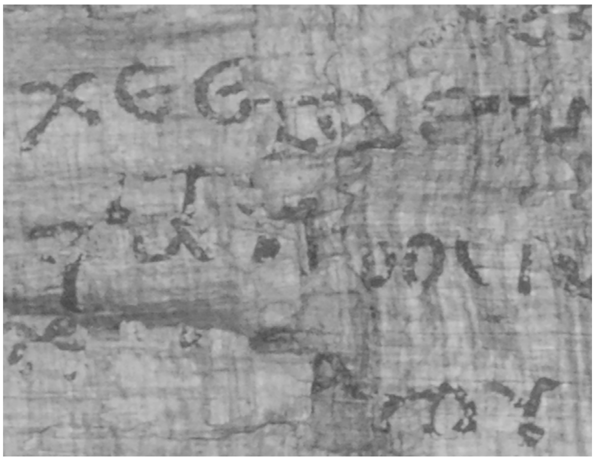
45 Examination was conducted visually on a Retina Display MacBook Pro with 15.4-inch colour display with 2880×1800 native resolution at 220ppi.

46 Malzbender et al. (2001).

47 See also Janko (2016). Note that the uncredited NIR-RTI research results discussed on p. 126 and illustrated in fig. 5 are the work of the present author while in the employ of Universität zu Köln, and the present publication constitutes the primary publication of that work.



a.



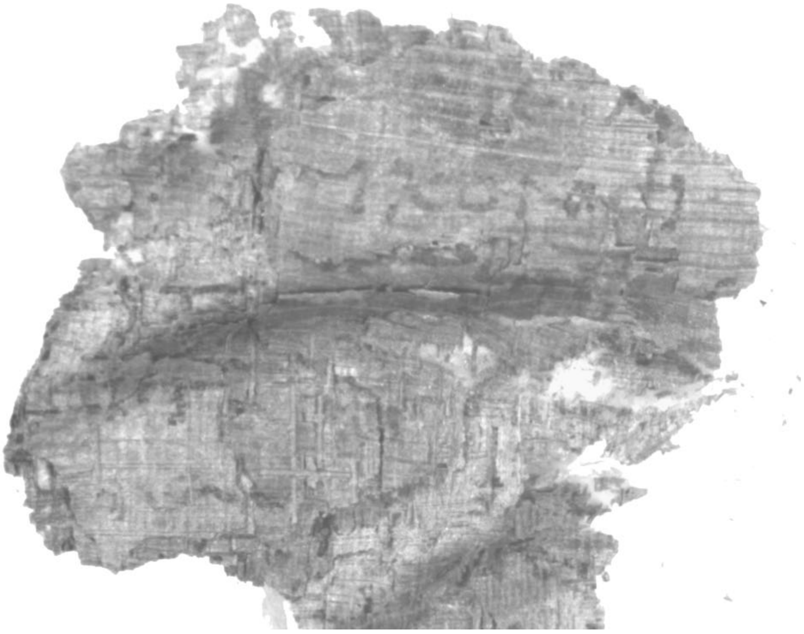
b.

c.

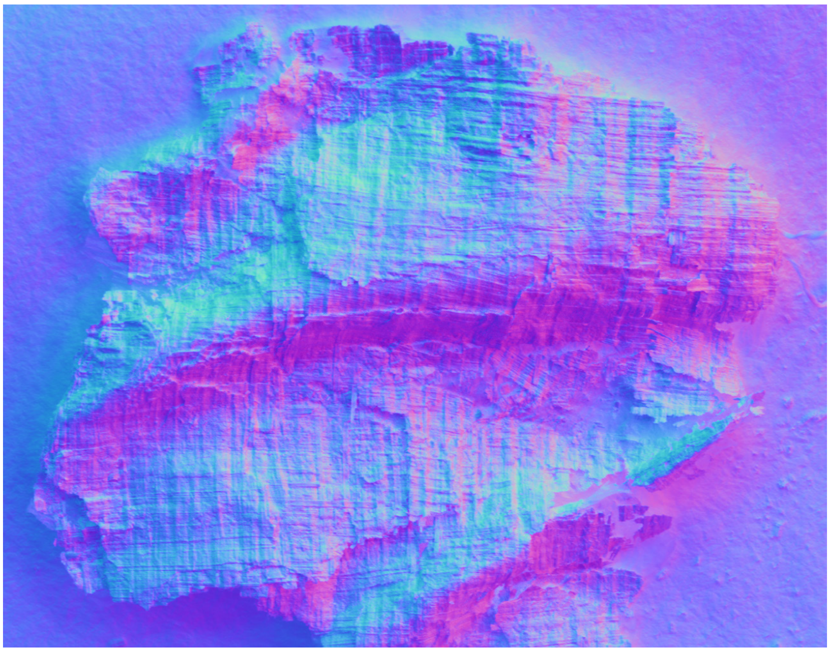
d.

Figure 7: PHerc. 862, Cornice 01, Pezzo 01. a. NIR photograph (950nm) (Brigham Young University, courtesy Biblioteca Nazionale di Napoli). b. Detail. c–d. RTI details, Specular Enhancement rendering mode with light in different positions showing physical structure and relationship between ink and layers (Kathryn E. Piquette, courtesy Biblioteca Nazionale di Napoli).

Writing previously lost in the dark folds of crumpled fragments can be illuminated. Movement of the light also enables the user to clearly distinguish the edges of dark features such as holes that may be confused with ink or where apparently continuous ink sits on different layers.[48] Likewise, by zooming in and slowly moving the light around an area of interest at low angles, the edges of papyrus layers can be iteratively and systematically traced (Figure 7). The normals visualisation mode offers easier discernment of misplaced fragments, showing in detail the micro-morphology of the pith including the direction and width of the fibres (Figure 8) – data that could aid fibre matching and virtual reconstruction in the future.[49]



a.



b.

Figure 8: Detail of PHerc. 1506, Cornice 01, Pezzo 01. a. NIR photograph (950nm) (Brigham Young University, courtesy Biblioteca Nazionale di Napoli). b. Normals Visualisation showing the high degree of micro-geometry that can be captured with NIR H-RTI (Kathryn E. Piquette, courtesy Biblioteca Nazionale di Napoli).

48 See Janko (2016), 124, fig. 4.

49 See also Stökl Ben Ezra (2014), 95–96; Tov (2015), 267–288.

NIR RTI also enables more comprehensive, systematic and in-depth remote study. Visualisation modes and bookmarking and annotation tools such as those in the Cultural Heritage Imaging RTIViewer[50] play a particularly critical role in supporting processes of "seeing" and "knowing". Observation conditions and viewing experiences that have long been subjective and personal can now be recorded, shared and replicated, making the research endeavour more robust and potentially more collaborative and transparent.[51] Because the RTI images are very high-resolution and visualisations provide excellent contrast and a superb record of surface shape and texture, in-depth desk-based research can be undertaken prior to first-hand inspection in Naples – if not removing this necessity entirely in some cases. By potentially reducing the need and length of time for handling, NIR RTI can perform a valuable preservative function by minimising papyrus document movement and consequent deterioration from exposure to light and other environmental changes, as well as reducing demands on library and conservation staff time. RTI also offers exciting potential for democratising access to the unrolled Herculaneum papyri, given that RTI viewing software is freely available and easy to use.

6. Future Directions

NIR RTI offers a power tool for studying the unrolled Herculaneum fragments, as a complement to both previous documentation and first-hand study. In order to exploit the potential of this technique on the large scale required for the corpus, certain technical challenges need to be met. Highlight RTI can be relatively time-consuming. For imaging large quantities of papyrus fragments/*cornici* with similar visualisation requirements at a set resolution, hardware and software that allow for semi-automated capture and processing will doubtless reap time-cost savings and ensure standardisation in data capture and metadata collection – similar to the way in which many RTI lighting dome systems operate.[52]

A current limitation of RTI is that, depending on camera sensor size and the size of the smallest significant character or other feature to be resolved, up to eight separate capture sequences would be required to image one *cornice*. Each capture sequence is self-contained and at present this subjects the user to the cumbersome procedure of opening multiple RTI files to view the contents of a single *cornice*. A key hardware and software development would be, therefore, to build into the design the ability to automate stitching of multiple RTI sequences.[53]

Another important aspect of future work is the documentation of the full 3-dimensionality of the papyri fragments.[54] A great advantage of RTI is its ability to record colour and 3D shape information, but it does not provide full metric data. Such quantitative information is essential for analysing papyrus layer relationships, correcting surface/sign distortion, and facilitating virtual hypothesising and reconstruction of sections/scrolls. Just as *sovrapposti* and *sottoposti* are fragments no longer in their original positions, the position of fragments mounted on the *cartoncino* cannot be assumed to be correct.[55] It is here that 3D models of the fragments would

50 http://culturalheritageimaging.org/What_We_Offer/Downloads/View/ (accessed 25 May 2017)

51 For detailed research into the processes by which users/experts 'read' texts and insight into the supporting role of visualisation and other technology, see Terras (2006); see also Tarte (2014) and (2011); Janko (2016) is also relevant here.

52 E.g. Earl et al. (2011).

53 The feasibility of stitching has been confirmed by Tom Malzbender (pers. comm. January 2015), albeit in one dimension only.

54 Cf. Pal et al. (2013).

55 Capasso (1991); Essler (2006); see also Hendriks (2015).

contribute tremendously to virtual reconstruction. A future imaging system should therefore also encompass the acquisition of true 3D data through photogrammetry or a similar technique. Another key to virtual reconstruction is fragment joining. Edges have suffered loss from scroll opening and mounting and further attrition unavoidably occurs due to environmental instability and handling of these extremely friable and delicate objects. Edge refitting presents a particularly difficult challenge and while it can be tackled to some extent by comparing written content, there is potential for computer algorithms to aid general shape matching while simultaneously exploiting papyrus fibre patterns and distribution.[56] More research is also needed to determine what spectral analysis of the substrate, including the papyrus material and adhesives used to join papyrus sheets together (e.g. PHerc. 994, Cornice 09), and constrate (including pigments, binders, and possible drying agents or other ingredients, e.g. lead[57]), can offer. Likewise, it is important to establish the extent to which non-destructive optical imaging can penetrate the upper layer(s) and where interrogation of substrata must await further development of penetrative techniques.[58] Much stands to be gained with a customised UV-VIS-NIR lighting and filter system, and one than allows integrated capture with RTI[59] and photogrammetry. Further, among various digital tools for facilitating scholarly and conservation work is a way to measure the x-y-z coordinates of, and between, points. Functionality that also allows areas of papyrus to be segmented and repositioned virtually, ultimately for scroll reconstruction, will be important. Similar to annotation and view bookmarking tools in the RTIViewer (above), a method of 3D model annotation would also be needed to support the research workflow, for example, for hypothesising scroll reconstructions or content meaning and indicating levels of interpretive certainty.

Thanks to advances in digital photography during the 1990s, great strides have been made in research on the unrolled Herculaneum papyri. With further developments over the past decade and a half, we are poised to take another leap forward. As the results of this pilot imaging project demonstrate, the integration of spectral photography with the RTI capture technique, together with photogrammetry, presents great promise for furthering the work of Herculaneum papyrologists and facilitating greater access to the fragile remains of the only surviving library from the classical world.

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56 The analytical potential of fibre patterning and distribution would be doubled if the backs of the uppermost layer could be recorded. Research we are currently undertaking at the UCL Centre for Digital Humanities ("Deep Imaging Mummy Cases" (https://www.ucl.ac.uk/dh/projects/deepimaging) led by Melissa Terras and Adam Gibson) is using spectral imaging on multiple layers of (uncarbonised) inscribed papyrus, and tests have shown that turning the papyrus so the upper pith fibres run parallel to the light direction reduces self-shadowing, making the underlying pith fibres, which run perpendicular to the light source, more visible..

57 Brun et al. (2016).

58 E.g. Mocella et al. (2015); Seales et al. (2011).

59 E.g. Hanneken (2016).

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