Application of Astronomical Imaging Techniques to *P.Herc.* 118
Russell A. Stepp and Gene Ware

The volcanic eruption that destroyed Pompeii in AD 79 also destroyed the nearby town of Herculaneum with pyroclastic deposits, which preserved a number of salient features of this Roman town. Among the most significant archeological finds at this site was a large villa containing a large number of ancient papyrus scrolls. While the volcanic eruption preserved these documents, the resulting moist heat carbonized the papyri and left them blackened and brittle. As a result, these scrolls have been very difficult to unroll and read.

The scroll labeled *P.Herc.* 118 is one of the many found in the ruins of the Villa of the Papyri. This papyrus, discovered at the site in 1752, was later gifted to the Prince of Wales in 1810 before being returned to Italy to be unrolled in 1883–1884. The unrolled scroll, in twelve primary pieces, is now housed at the Bodleian Library in Oxford, England, but is damaged and carbonized to the extent that the majority of the document is illegible.

In April 2005, Gene A. Ware of Brigham Young University conducted a pilot project to create Multispectral Images of the papyrus. This initial investigation was followed by a more extensive session in August of the same year. The purpose of this project was twofold: first, to capture and digitalize images of this papyrus to make it available to scholars worldwide; and second, to apply Multispectral Image (MSI) processing techniques to the images with the hope of improving the readability of the text contained on the papyrus.

The images of the papyrus were collected by Ware in August 2005 using a system comprised of a "digital camera, filter wheel, lens, control computer, XY positioning table, lights, tripod, and other associated equipment." Four near infrared and three RGB images were captured on the Kodak 4.2i Megaplus scientific-grade digital camera with a 2033 x 2044 array with three defective pixels (Figs. 2–8).

The images recorded at position X01Y05 from frame two of *P.Herc.* 118 were chosen for initial processing. This region of the text (Fig. 1), taken from a color photograph from the Bodleian Library, was selected because it is one of the few in which text is visible at all, and the choice of such a region facilitates a comparison between the ink and background papyrus. The clearest individual image is the image shot at 950 nm. The seven Multispectral Images of *P.Herc.* 118 were processed principally through the use of the IRAF software to further enhance readability by processing the images as a group.

The first phase of the image processing involved an analysis of the spectral character of selected regions of the image. Different information about the character of the text and the background is contained at each wavelength, however it is not usually apparent to the naked eye. The nature of this information

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2 Ibid., 46.
3 The Bodleian Library, <http://image.ox.ac.uk/show?collection=bodleian&manuscript=msgrclassb1p112>.
4 G. Ware, *Preliminary Data Report: Multispectral Images of Bodleian Ms. class. B. 1 (P)/1–12 P.Herc. 118* (Provo 2005) 4. A complete discussion of the image collecting process is available in this report.
must be properly understood in order to efficiently produce images with increased legibility as seen by the human eye. This initial analysis of the spectral character of the multispectral images was achieved through application of aperture photometry and the PHOT function within IRAF.

The PHOT function converts a small diction of an image into an astronomical magnitude, a system used in astronomy to quantify the brightness of stars. This scale is inverted and logarithmic, with a lower magnitude indicating a brighter star, and stars with a magnitude difference of 1.0 differ in actual luminosity by a factor of ten. To use the PHOT function, the user first creates a small aperture around a star, and the PHOT command converts the number of photon counts within the aperture into a magnitude. In place of stars, small sections of ink and papyrus of *P.Herc. 118* were selected and the PHOT function was applied to these regions in order to obtain an astronomical magnitude.

Four principal regions were identified in the papyrus for analysis: the ink, cracks in the papyrus, light areas of papyrus, and dark areas of the papyrus. These regions were selected by examination of the 950 nm image, as it appeared to show the greatest distinction between these four regions. Forty-five apertures were placed on regions of ink, thirteen on cracks, and twenty on regions of light and dark papyrus. The apertures were set at a fixed radius of two pixels, which seemed to be sufficient to enclose a maximum area of text or crack with a minimal overlap to the surrounding papyrus. The locations of these apertures are shown in Figures 9–12. A series of curves depicting the average values of the resulting magnitudes are depicted in Figure 1.

These spectral reflectance vectors are supplemented by creating contrast or modulation curves for the infrared and RGB data. There is a positive correlation between readability and contrast. A contrast equation 1 was applied to the average values for the regions of dark papyrus and ink to indicate regions of improved readability.

\[ C = \frac{m_I - m_P}{m_I + m_P} \]

In this equation \( m_I \) and \( m_P \) correspond to the magnitude of the regions of ink and papyrus respectively. \( C \) represents the contrast between two values, with a higher value representing greater legibility. Equation (1) was applied to the raw magnitude data and the resulting contrast curves are represented in Figures 2 and 3.

While this analysis demonstrates a greater distinction between text and papyrus at 950 nm than any of the other wavelengths, the RGB data indicates only slight differences between text and background, with the dark text and ink being virtually identical in the blue filter. This analysis also shows a spike in light absorption in the cracks of the papyrus at 900 nm, a behavior that differs strongly from the surrounding text and papyrus.

The second stage of the analysis of the *P.Herc. 118* images involved the application of the IMARITH package in IRAF. Since the reflectivity of the regions of papyrus differs slightly in each filter, image arithmetic can be used to enhance the contrast of important features of the image, while simultaneously reducing other features which diminish the readability of the text. Since the final step in processing these images involves interpretation by a human viewer, the final goal of application of image arithmetic is
somewhat subjective. As a result, there are no concrete mathematical criteria for determining whether an image is an improvement over the unprocessed images and as a result the final determination of whether one image is more legible than another is ultimately left to the somewhat subjective judgment of a human reader.

The spectral reflectance vectors and contrast curves show the greatest contrast between text and image in the 950 nm filter, and the smallest in the blue filter, and so it is natural to use these frames as the basis for image arithmetic. A simple subtraction of the blue image from the 950 nm image increased the readability of the 950 nm image, but further processing provided even more successful results. Subtraction of an inverted image from the original image always led to improved readability. Application of this process to the 950 nm image combined with an additional subtraction of a red, green, or blue image produced a more readable image. In general improved legibility was consistently demonstrated through a simple algorithm represented by the following series of arithmetical operations:

$$950 \text{ nm} - \text{Green} - \frac{1}{950 \text{ nm}}$$

Further arithmetical functions beyond this basic algorithm can produce even better results, but no single series of operations consistently demonstrated increased legibility. However, the following three points provide a series of useful arithmetical functions, and excepted results, which can be applied with a series of multispectral images:

1. Multiplication by a constant: This increased readability of certain regions of text, but tended to simultaneously decrease the readability of others.
2. Squaring an image: This increased the contrast between text and papyrus, and while useful, appears to be a feature possible on a number of more common graphics editors.
3. Additional subtractions of other selected images: This was occasionally useful for increasing readability, but no accurate method of predicting future behavior was discovered. Some subtractions actually decreased the readability of the image.

Figures 13–18 provide a selection of postprocessed images which demonstrate improved legibility over not only the original photograph, but also over any of Ware's original photographs.

Images processed through image arithmetic show a clear improvement over not only the \textit{P.Herc. 118} manuscript, but also over any single filter image. The top right corner of these images reveal a clear \textit{sovraposto}, a layer of papyrus attached to the unrolled layer. This \textit{sovraposto} is visible in the original infrared images, but is much clearer in the processed images, and contains clearer text than on any of the unprocessed images. Finally, the lower right section of the section of these images reveals text not clearly visible on any of the original frames.

The application of astronomical image processing techniques to the \textit{P.Herc. 118} papyrus images has revealed previously unknown information about the papyrus and text. Prior to this study, no true MSI processing had been conducted on any of the Herculaneum papyri. The analysis and results provided herein form a basis for understanding how the papyrus and ink respond to different wavelengths of light. This understanding can further be enhanced using a spectrograph to obtain high-resolution spectral data
of the papyrus and ink, achieving an even deeper knowledge of the spectral characteristics of these documents.

The reflectance spike noted at 900 nm in the cracks, as well as the overall shape of the ink's spectral profile is in need of further study. The 900 nm reflectance spike, if further quantified, may prove to be a significant tool for distinguishing minute papyrus cracks from ink. Additionally, a higher resolution definition of the ink's spectral reflectance could be correlated with other regions of uncertain composition to distinguish between ink and background.

The processed images revealed features of the document not clearly visible in any of the original images. The application of image arithmetic has been successful, and can often lead to increased contrast or readability. However, beyond a few simple operations, there is no fixed sequence of image arithmetic which will achieve maximum readability on all papyri. Each region of the papyrus will need be processed on a case-by-case basis, preferably with the assistance of a scholar who is able to read the Greek text of the papyrus and provide feedback.

Fig. 1
Real-color photograph of the selection of the *P.Herc.* 118 papyrus investigated in this study
Fig. 2

*P.Herc. 118* photographed through a red filter

Fig. 3

*P.Herc. 118* photographed through a green filter
Fig. 4

*P.Herc.* 118 photographed through a blue filter

Fig. 5

*P.Herc.* 118 photographed through a narrow bandwidth filter centered at 950 nm
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\textbf{Fig. 6}

\textit{P.Herc.} 118 photographed through a narrow bandwidth filter centered at 900 nm

\textbf{Fig. 7}

\textit{P.Herc.} 118 photographed through a narrow bandwidth filter centered at 850 nm
Fig. 8

*P.Herc.* 118 photographed through a narrow bandwidth filter centered at 800 nm

Fig. 9

Location of apertures place on regions of ink
**Fig. 10**
Location of apertures placed on regions of light papyrus

**Fig. 11**
Location of apertures placed on regions of dark papyrus
Fig. 12
Location of apertures placed on regions of cracks in the papyrus surface

Fig. 13
Post-processed image
Fig. 14
Post-processed image

Fig. 15
Post-processed image
Fig. 16
Post-processed image

Fig. 17
Post-processed image
Fig. 18
Post-processed image