Notes and Communications

Enhancement of Document Legibility Using Spectroscopic Imaging*

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RÉSUMÉ Cet article décrit l'application de l'imagerie spectroscopique dans la région de longueur d'onde infrarouge proche afin d'examiner deux parchemins historiques. Cette méthode d'analyse optique non destructive permet de distinguer des différences subtiles dans les propriétés du facteur de réflexion des matériaux étudiés. Trois zones des parchemins ont été sélectionnées pour l'étude, montrant trois caractéristiques particulières : de l'écriture pâle, des lignes épaisses intercalées avec de l'écriture pâle et du texte obscurci par des corrections. Les mesures consistaient en séries de 41 images numériques en bandes étroites prises à intervalles de longueur d'ondes de 10 nanomètres entre 650 et 1050 nm. Chaque image en bande étroite était constituée de 256 par 256 pixels et représentait les valeurs de l'intensité du facteur de réflexion d'une longueur d'onde particulière. Plusieurs types de manipulations numériques ont été utilisées afin de traiter les données. La lisibilité de l'écriture pâle a été améliorée grâce à la soustraction, pixel par pixel, d'images prises à différentes longueurs d'ondes. La même méthode a été utilisée pour distinguer les réponses spectrales du facteur de réflexion des lignes épaisses et de l'écriture pâle. Le texte obscurci par des corrections a été rendu lisible en utilisant l'analyse en composantes principales pour la série complète des 41 images en bandes étroites. L'affichage de toutes les images obtenues grâce au traitement utilisant les fausses couleurs a rendu toutes les images traitées plus faciles à interpréter visuellement. L'article décrit les applications possibles pour l'étude des manuscrits dans un mauvais état de conservation.

ABSTRACT The article describes the application of spectroscopic imaging in the near-infrared wavelength region to examine two historical parchments. This non-destructive

* Author's email address: attasm@aecl.ca. This work could not have taken place without the enthusiastic assistance of Carl Bigras and others at the Canadian Conservation Institute in Ottawa, and Abigail Quandt at the Walters Art Museum in Baltimore, who made the parchments available. I am also grateful to James Mansfield, my predecessor at the Institute for Biodiagnostics, who pioneered the application of spectroscopic imaging to works of art, and to Henry Mantsch, who encouraged me to continue Jim's work there. With Ed Cloutis, Doug Goltz, and Claudine Majzels at the University of Winnipeg, and Cathy Collins at the Winnipeg Art Gallery, we have continued our collaboration by establishing C-SCAPE, the Centre for Scientific and Curatorial Analysis of Painting Elements, based at the University of Winnipeg. Numerous insightful comments by Ino Attas and two anonymous reviewers have led to significant improvements to the text of the paper.

optical method of analysis can distinguish subtle differences in the reflectance properties of the materials under study. Three areas on the parchments were selected for study, showing three types of features: faint writing, heavy lines interspersed with faint writing, and text obscured by corrections. The measurements consisted of sets of 41 narrow-band digital images taken at 10-nanometre wavelength intervals from 650 to 1050 nm. Each narrow-band image consisted in turn of 256 by 256 pixels representing reflectance intensity values at a particular wavelength. Several types of numerical manipulations were used to process the collected data. The legibility of the faint writing was increased through pixel-by-pixel subtraction of images taken at different wavelengths. The reflectance spectral response of the heavy lines was distinguished from that of the faint writing in the same way. The text obscured by the corrections was made readable using principal-components analysis of the entire set of 41 narrow-band images. Displaying all the images resulting from the processing using false colour made all the processed images easier to interpret by eye. Possible applications to the study of manuscripts in a poor state of conservation are described.

Introduction

Reading a poorly preserved document requires skill, experience, and patience. Although technical aids are no substitute for these human characteristics, they can usually make the reading easier. Sufficient lighting and a magnifier are simple and common tools for this job. More difficult readings may require more elaborate techniques in order to reveal faint ink marks, or to compensate for the effects of damage to the document, or both.

A prerequisite for reading text is to sort out exactly where the text is, i.e., to distinguish the writing from the background. The unaided human eye is able to pick out subtle colour variations, but its job is made easier by digital imaging techniques, consisting of acquisition and of processing. Methods of processing images after they have been acquired are now quite widely known. Adjustments to the brightness, contrast, and colour balance of an image are now within the capabilities of any amateur photographer with access to a computer. These adjustments can result in significant improvements to legibility when used on their own. But when combined with specialized image acquisition technology, their impact can be much greater. Since the acquisition technology is less familiar, it deserves more detailed description.

Our eyes and brain give us the sensation of colour by combining nerve stimuli from only three types of sensors ("cones") in the retina, sensitive to the wavelengths of light we perceive as red, green, and blue.[1] Our perception and appreciation of all colours are generated in the brain from combinations of the signals from these three types of sensors. Imaging technology expands this wavelength range by providing additional sensitivity, especially to parts of the spectrum that our eyes do not respond to: the ultraviolet and infrared regions.

1 K. Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color* (New York, 1983).

The advantages of looking at the reflectivity of pigments and other materials under light from the near-infrared region (wavelengths beyond 700 nanometres, or nm) has been investigated by many researchers.[2,3,4] Also, a plot of reflectivity as a function of wavelength (i.e., the near-infrared spectrum) may be helpful in distinguishing pigments. Light beyond the other end of the visible spectrum can also be used to enhance the legibility of ink on parchment. Illumination with ultraviolet light (wavelengths less than 400 nm) makes the parchment around the ink fluoresce in blue, thereby increasing the contrast between the dark ink and the bright ground.[5]

The information contained in a spectrum plotted within the range of visible colours (400 to 700 nm) is also valuable in the investigation of pigments, and in distinguishing ones that appear similar to the eye. This is because spectroscopic measurements collect information on reflectivity not just for red, green, and blue but also for spectral colours in between. Pigments appearing similar to each other, or similar to the background colour, may show differences in their spectra that allow them to be separated. Visible-light spectroscopy of pigments is a well-established field of investigation.[6,7]

Spectroscopy and digital imaging can be combined by using image sensors that have direct sensitivity to more colours than simply red, green, or blue.[8] Combining multiple views of an object made using several colours of illumination (or equivalently, combining multiple views imaged through several colours of filters) is known as multispectral imaging. This technique has been successfully adapted from the world of remote sensing to many other fields, including biological and industrial applications.[9] It can be an advantage in

2 A. Richards, *Alien Vision: Exploring the Electromagnetic Spectrum with Imaging Technology* (Bellingham, WA, 2001).

3 C. Baker, "A Comparison of Drawing Inks Using Ultraviolet and Infrared Light Examination Techniques," in P. A. Englander and L. van Zelst, eds., *Application of Science in Examination of Works of Art* (Boston, 1985), pp. 159–63.

4 J.R. Mansfield, M. Attas, C. Mazjels, E. Cloutis, C. Collins, H.H. Mantsch, "Near Infrared Spectroscopic Reflectance Imaging: A New Tool in Art Conservation," *Vibrational Spectroscopy* 28 (2002), pp. 59–66.

5 A. Quandt, "The Archimedes Palimpsest: Conservation Treatment, Digital Imaging and Transcription of a Rare Mediaeval Manuscript," in V. Daniels, A. Donnithorne, and P. Smith, eds, *Works of Art on Paper: Books, Documents and Photographs: Techniques and Conservation* (London, 2002), pp. 165–71.

6 M. Bacci, "Fibre Optics Applications to Works of Art," *Sensors and Actuators* B29 (1995), pp. 190–96.

7 J. Goupy and J.-P. Mohen, eds., *Art et chimie, la couleur: Actes du congrès*, (Paris, 2000).

8 R.S. Berns, "Visible-Spectrum Imaging Techniques: An Overview," *AIC Color 01, Proceedings of the 9th Congress of the International Colour Association*, SPIE 4421 (Bellingham, WA, 2002), pp. 475–80.

9 P. Colarusso, L.H. Kidder, I.W. Levin, J.C. Fraser, J.F. Arens, E.N. Lewis, "Infrared Spectroscopic Imaging: From Planetary to Cellular Systems," *Applied Spectroscopy* 52 (1998), pp. 106A–120A.

several ways for document investigations. For example, charred or otherwise damaged documents can sometimes be more easily read when examined using specific colours of light. A good example of an application to ancient materials is its use to examine carbonized papyri from Herculaneum.[10] A more elaborate variation of that technique is known as hyperspectral imaging, which involves collecting a large number (at least several dozen and sometimes hundreds) of images at regularly spaced wavelength bands. It too has become successful, first in remote sensing and then again in other fields, including investigations of fragments of the Dead Sea Scrolls.[11] When used to analyze the colours of light reflected from objects, these techniques are collectively known as reflectance spectroscopic imaging. The basic tenet of spectroscopic imaging is that a collection of images of a scene or object made at multiple wavelengths contains much more information than is evident from examination of any single image.

A useful concept in interpreting data from spectroscopic imaging is to consider the collection of single-wavelength images as a single, three-dimensional data set, or data cube (Figure 1). Two of the dimensions are spatial, as they represent location on the surface of the object; i.e., the pixel position. The third, or spectral, dimension represents the wavelength. In other words, the data value (number) at each pixel is the measured intensity of light at a particular wavelength reflected from that particular point on the surface of the object. The 3-D data cube can be considered as a stack of images, and at the same time as a two-dimensional array of many low-resolution spectra, one for each pixel (Figure 1). The spectra give information on the reflectance properties of the sample at each point in the image. Different reflectance properties are usually the result of different chemical compositions. For art and document investigations, the composition of pigments is of considerable interest, and distinguishing among them can provide evidence of alterations. For manuscripts, the differences in the reflectance of the ink from that of the background (the parchment, paper, or papyrus support) can be used to enhance the legibility of the writing, inks of different composition can be distinguished, and the effect of distractions or obscurations caused by flaws in the background (e.g., dirt, stains, mold) or by subsequent additions can be reduced. All these enhancements are of use to the archivist in reading the manuscript.

Several years ago, in collaboration with other Winnipeg researchers, the NRC Institute for Biodiagnostics expanded its use of reflectance spectroscopic imaging beyond the study of biological tissues to apply it to works of

10 H. Baumgartner, "New Light on Ancient Scrolls," *Mechanical Engineering* (April 2002).

11 G.H. Bearman, S. Pfann, S. Spiro, "Imaging the Scrolls: Photographic and Direct Digital Acquisition," in P. Flint and J. Vanderkam, eds., *The Dead Sea Scrolls after Fifty Years: A Comprehensive Assessment* (Brill, 1998), pp. 472–95.

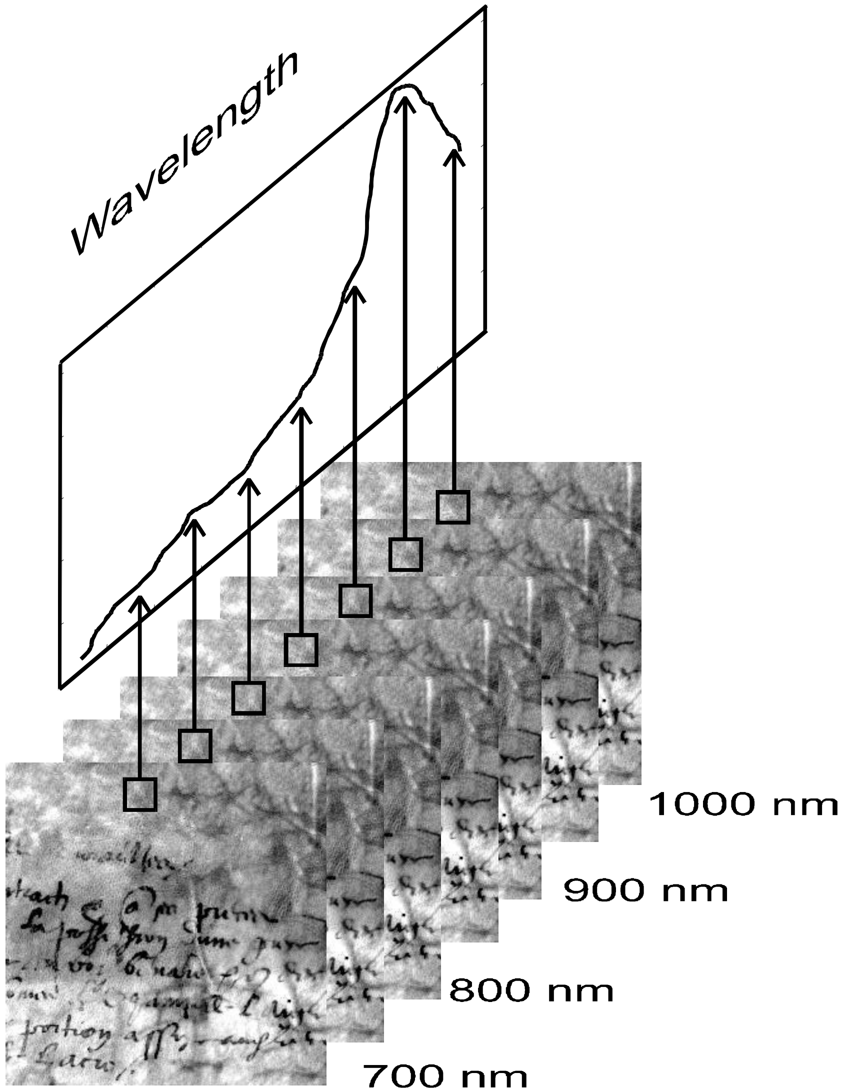

Figure 1 Image data cube.

art.[12,13,14] The techniques for acquiring and processing the image sets were adapted with minimal changes from the Institute's biomedical work. Recently, the opportunity arose to apply hyperspectral-imaging techniques to the examination of two manuscripts on parchment supports. This note summarizes our findings to date.

Materials and Methods

Sample Parchments

The senior conservator at the Walters Art Museum in Baltimore, Abigail Quandt, had lent several parchments to the Canadian Conservation Institute in Ottawa for study. Carl Bigras of that Institute transported two of them to Winnipeg for a day's examination, which took place at the Institute for Biodiagnostics on 15 March 2002. The first document is written in French, on both sides of a folded sheet of parchment, using brown ink that is so faint at various points that it is difficult to read. In several areas it has heavier lines between the lines of text, and some very faint gray rulings. The second document, written in English, has much clearer text but also contains several corrections, which completely obscure the underlying text in a few places. Together they provided a reasonable variety of legibility problems on which to test our hyperspectral imaging technique. Details of the physical and historical nature of these parchments will be published elsewhere.[15]

Instrumentation

The optical instrumentation itself was identical to that used for biomedical imaging. Its key components, designed to facilitate collection of multiple images at different wavelengths, are a tunable near-infrared filter and a high-sensitivity digital CCD camera. Our custom-assembled instrument used a MicroMAX scientific digital camera made by Roper, Inc. (Princeton, NJ), and incorporating a frame-transfer CCD sensor. The thermoelectrically cooled

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12 J.R. Mansfield, M.G. Sowa, C. Mazjels, C. Collins, E. Cloutis, H.H. Mantsch, "Near Infrared Spectroscopic Reflectance Imaging: Supervised vs. Unsupervised Analysis Using an Art Conservation Application," *Vibrational Spectroscopy* 19 (1999), pp. 33–45.

13 M. Attas, E. Cloutis, C. Collins, D. Goltz, C. Majzels, J.R. Mansfield, H.H. Mantsch, "Spectroscopic Imaging in Art Conservation: A New Tool for Materials Investigations," *Leonardo* 36 (2003), pp. 304–7.

14 M. Attas, E. Cloutis, C. Collins, D. Goltz, C. Majzels, J.R. Mansfield, H.H. Mantsch, "Near-Infrared Spectroscopic Imaging in Art Conservation: Investigation of Drawing Constituents," *Journal of Cultural Heritage* 4 (2003), pp. 127–36.

15 R. Scott Williams, Canadian Conservation Institute, personal commentary, 23 May 2002.

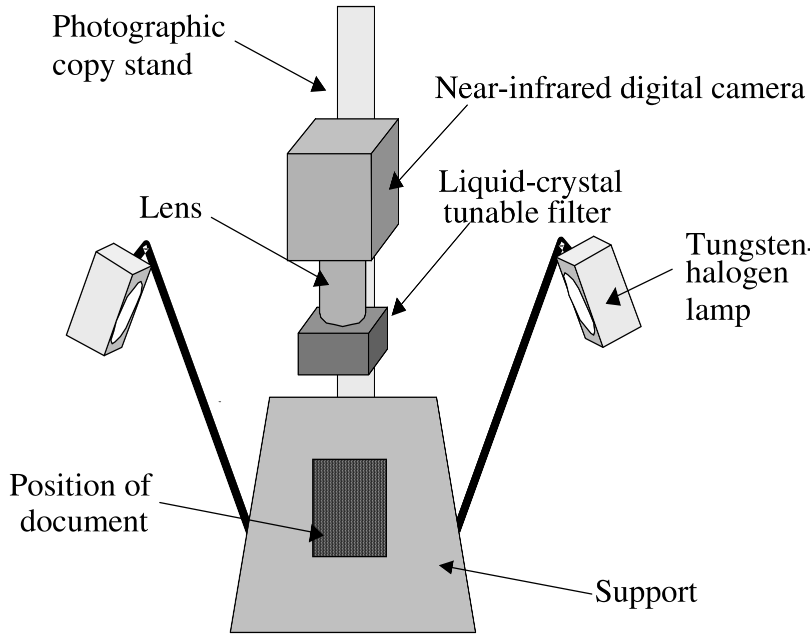


Figure 2 Sketch of instrumentation.

sensor of that camera has square pixels 13 μm on a side, arranged as a square array of 512 × 512 pixels. The camera was fitted with a Nikkor photographic macro lens (Nikon, Japan), on the front of which was mounted a Varispec liquid-crystal tunable filter (Figure 2). The filter (CRI, Inc., Woburn, MA) has an operating range of 650–1050 nm, with a nominal bandpass of 7 nm, and a transmission varying from 10% to 50%. Both the camera and the filter were controlled by a personal computer, which was also used for data collection. The filter was operated through custom LabVIEW software (National Instruments, Dallas TX), which also handled the image acquisition. The standard image cube consisted of 41 images (each a 200-ms exposure) taken at wavelength intervals of 10 nanometres from 650 to 1050 nm. Overall acquisition time was approximately 2 minutes. To save disk space and processing time, the image sizes were reduced to 256 by 256 pixels by binning, or combining the contents of adjacent pixels.

For manuscript imaging, the camera/lens/filter assembly was mounted on a photographic copy stand, pointing vertically downwards (Figure 2). Two incandescent lights were directed at the parchment, which lay flat on the stand's base. The intensity of the lights was adjusted by setting voltage controllers low enough that most of the light emissions were in the near-infrared range. The wavelength at which the light intensity was greatest was determined to be approximately 850 nm. As part of the calibration of the instrumentation, a white cardboard Kodak reflectance standard was imaged under the exact conditions of the subsequent parchment imaging. This sheet of relatively high and uniform reflectance served as a reference, to correct the data for variations in filter transmission, pixel sensitivity, and other optical non-uniformities.

Data Processing

After acquisition, the data files corresponding to the sets of images were transferred to another computer for processing using the general-purpose mathematical software package MATLAB (The MathWorks, Natick, MA). Each data cube occupied 10.5 megabytes. Simple routines have been written for taking the pixel-by-pixel ratio of intensities between the parchment and the reference card, as well as for displaying images at single wavelengths for visual examination, adjusting contrast and brightness, using colour mapping, and calculating sums, differences, and ratios of images.

Additional processing was performed using algorithms specific to spectroscopic imaging, as provided by the remote-sensing package ENVI (Research Systems, Boulder, CO). In particular, its principal-components analysis (PCA) routine has proven effective for our purposes. The goal of PCA is to restructure a multivariate data set by replacing the original variables with new ones, called principal components.[16,17,18] The new variables are linear combinations of the original ones; in other words, sums of the scaled original values. They are generated so as to be mutually uncorrelated and to contain as much of the variance of the original data set in as few new variables as possible. For our data sets, the input data to the PCA calculation were the $256 \times 256 = 65536$ pixel intensity values at each of the 41 wavelengths (original variables), so the PCA algorithm generated 41 principal components (linear combinations of wavelength values).

The first principal component is the single linear combination that captures the most information content, the second one captures the next-most, and so on. As a result, the graphical (image) representations of the first few principal components are visually rich in structure. For spectroscopic imaging data, the first principal component highlights general trends in overall intensity, so its image looks similar to an average view of an object through all the 41 wavelengths. The second component highlights differences in reflected light inten-

16 J.F. Hair, R.L. Tatham, R.E. Anderson, W. Black, *Multivariate Data Analysis*, 5th ed. (Upper Saddle River, NJ, 1998).

17 L.G. Grimm, P.R. Yarnold, eds., *Reading and Understanding Multivariate Statistics* (Washington, DC, 1995).

18 P. Geladi, H. Grahn, *Multivariate Image Analysis* (New York, 1996).

sity at different wavelengths, so its image shows many contrasts between areas of different colour or composition. Sometimes the third and fourth components also highlight interesting contrasts, but beyond a certain number of principal components, all the useful information has already been accounted for, and the images of the subsequent ones show only electronic noise. The principal-components calculation, therefore, creates a more compact representation of the original image set, and separates the signal (information-containing) portion of the image data from the noise. Examination of the images representing the first few principal components is an effective way to rapidly absorb the information content of a spectroscopic image set.

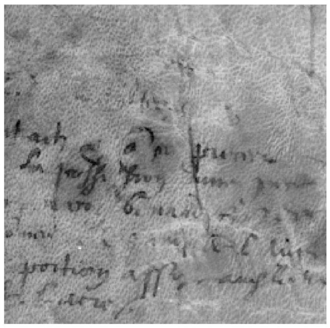
Results and Discussion

Simple Image Manipulations

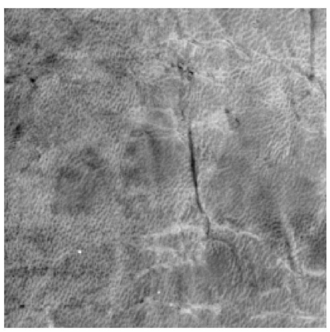
For each of the parchment areas studied, the first step was visual examination of the 41 single-wavelength images as displayed on a computer monitor. As we had noticed while acquiring the images, the contrast of the writing decreased with increasing wavelength (i.e., farther into the infrared spectral region). Although this might not appear to be directly useful for image enhancement, in some cases the near-infrared images were able to help highlight other features of interest. For example, the English parchment has gray (graphite?) lines ruled across the parchment to guide the scribe. With the writing less visible in infrared wavelengths, the ruled lines could be examined more easily.

Although the actual degree of improvement has not been quantified, the following comments are based on the opinions of several observers, who were not experts in manuscript interpretation. Basic techniques of image enhancement, in particular brightness and contrast adjustments on single-wavelength images, generally resulted in a slight improvement in legibility. More improvement came with pixel-by-pixel subtraction of near-infrared images from visible-light ones (e.g., the image resulting from the subtraction of the near-infrared 960-nm image from the red 660-nm one). This greatly reduced the distracting effects of unvarying features of the parchment such as stains, as well as the effects of uneven lighting and variations in surface height. With these distractions reduced, the writing itself was easier to read. The degree of enhancement was further increased when several images at adjacent wavelengths were averaged to improve the signal-to-noise ratio.

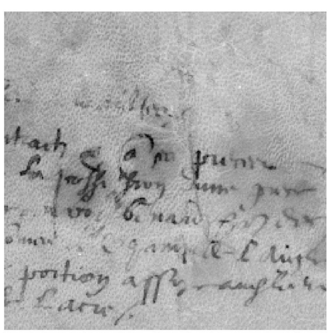
These observations are illustrated in Figures 3 and 4 for the French and English parchments respectively. In each case, the top image shows how the parchment would appear in red light, which is in fact quite similar to its appearance in natural light. The middle image shows its appearance in near-infrared light, where the ink is almost invisible, but the parchment texture and flaws are still clear. The result of subtracting that image from the red-light



650 + 660 nm (red) image

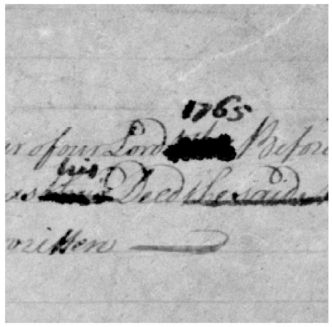


850+860 nm (near-IR) image

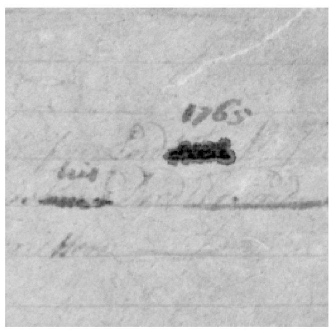


difference image

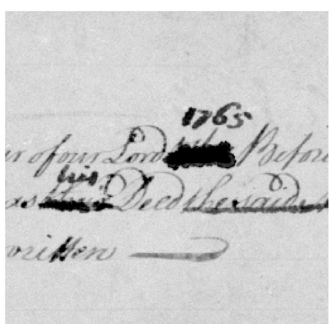
Figure 3 French parchment: narrow-band images in red and infrared.



650 + 660 nm (red) image



850+860 nm (near-IR) image



difference image

Figure 4 English parchment: narrow-band images in red and infrared.

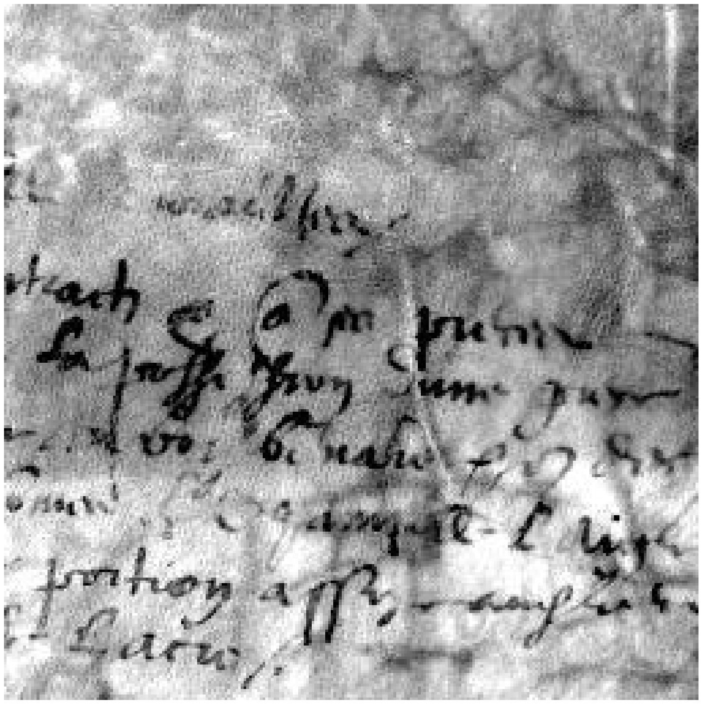


Figure 5 French parchment: image of principal component no. 2.

image is shown at the bottom of each figure. The background appears much more even, thereby enhancing the visibility of the text.

Principal Components Analysis

Principal components analysis was performed on the full set of 41 images for each parchment. The first principal component (PC#1, not shown) strongly resembled the naked-eye view. The second one highlighted the writing dramatically, because it displayed the maximum contrast between ink and parchment. The legibility of the faint writing in the French parchment (Figure 5) was thereby increased significantly, beyond the improvements brought about by the simple image manipulations.

For parchments with more than one type of ink, the third principal component also yielded useful results, in distinguishing the ink types. (Here "types" does not necessarily imply fundamentally differing chemical compositions, but at least somewhat differing optical properties in the near-infrared spectral region.) The English parchment had places where a date and word had been

Figure 6 English parchment: image of principal component no. 2.

obscured by ink with different characteristics. Although to the eye the correction completely blotted out the words written using the original ink, it was possible to read the underlying writing in the images generated using principal-components analysis, as shown in Figure 6. (It should be noted that the assignment of positive and negative sign to the principal-component data is arbitrary, so there is no significance to the fact that the writing is dark in Figure 5 but light in Figure 6.)

A standard technique for displaying multiple layers of visual information simultaneously is false-colour image generation. Up to three monochrome images can be displayed simultaneously by coding each using a primary colour. This allows up to three images acquired at three different wavelengths to be studied at the same time. The three images are displayed using red, green, and blue, respectively, thereby creating a colour image from their superposition. Our eyes and brain are well suited to distinguishing subtle differences in colour, to a better extent even than differences in monochrome shading, so changes in the relative intensities of the light at different wavelengths are highlighted. False-colour images of this type (not shown) were

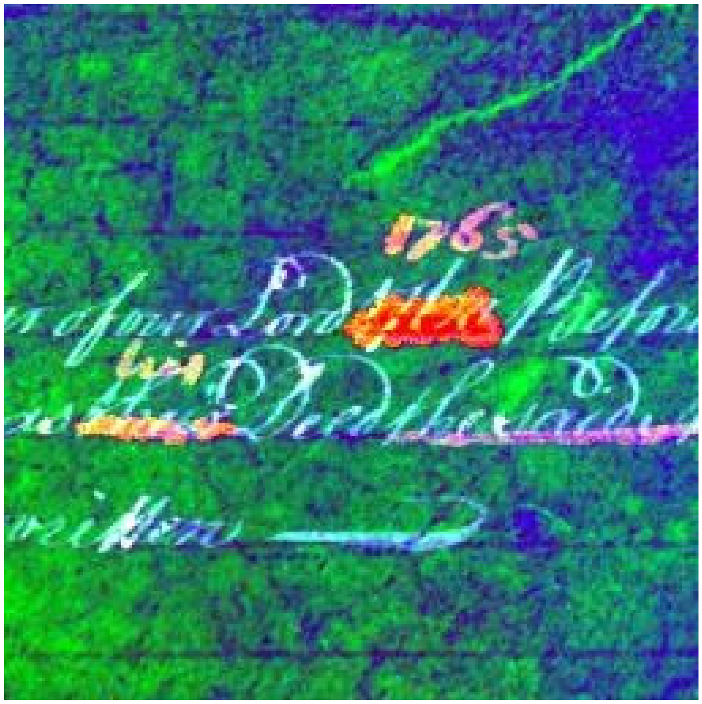


Figure 7 English parchment: image of principal components nos. 1, 2, and 3, coded as red, green, and blue.

produced from the parchment data, and were somewhat helpful in increasing legibility.

False-colour images can also be generated using three principal-components images as inputs instead of three single-wavelength images. In Figure 7, the false-colour image has conveyed all the information contained in the gray-scale images of principal components #1, #2, and #3, but in a single image. The original ink appears whitish, while the ink used for the correction appears orange to yellow. It is possible to read both simultaneously, in the same synthesized image.

Prospects

This limited trial has shown some of the power of spectroscopic imaging and principal components analysis for enhancing writing on parchment. Despite its success, it is very likely that neither the instrumentation nor the measurement parameters are optimal. Several approaches can be envisaged to improve the quality of the enhancements, or to reduce the cost of the process. Collection of images at additional wavelengths in the range 650–1050 nm, or beyond that range, would provide a more extensive data set, but it is yet to be determined whether the additional data would yield superior discrimination of the writing. On the other hand, it may be that fewer wavelengths would suffice, thereby reducing the file sizes and acquisition times. If adequate enhancement can be obtained using only a few wavelengths, then a less expensive filter wheel might serve for wavelength selection instead of the tunable filter. In any case, a digital camera with higher spatial resolution would improve the sharpness of the images, and allow a larger section of parchment to be imaged in one run. The images shown in this paper contain only 256 by 256 pixels; a camera with over a million pixels would be more appropriate for routine use. It should also be noted that the processed digital images show more detail and contrast when displayed on computer monitor than when printed on standard office equipment. Wherever possible, therefore, the interpretation of the results should be done using the digital image files displayed on a screen.

Limitations of the technique have not been examined explicitly in this study, but a few remarks are in order. Although the examples chosen were parchments, there is no reason that the technique would not be applicable to writing on other supports. Size and shape of the object being studied are not limitations since they can be accommodated by selecting an appropriate distance between the object and the camera. If necessary, a large object can be analyzed piecemeal and the images combined later using commercial "stitching" software. Depth of field may be a restriction for relatively uneven objects. As for regular photography, stopping down the lens (using a higher f-number) increases the depth of field, but decreases the amount of light reaching the sensor. To compensate for this, exposure times may be increased. Total exposure of the objects to light would remain on the order of a few minutes. If the objects are particularly sensitive to photothermal damage, this could be mitigated by filtering the light sources to remove the thermal (longer-wavelength) infrared component.

Conclusion

We have demonstrated that the spectroscopic imaging method is a useful tool for examining the writing on historical parchments. The method was shown to be valuable in enhancing the legibility of the text, as well as in enhancing alterations and obscured words when the obscurations have different optical properties. It has natural applications to the study of documents where the text is difficult to read, as well as in the field of forensics.