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Image Processing Methods that Reveal Erased Handwriting: Developments of the Last Two Decades*

INTRODUCTION

In the past, manuscripts that were no longer of interest to their owners were erased and overwritten. The erased writings of these manuscripts, i.e. the palimpsests, are often hundreds of years older than the visible overwriting on the manuscripts and may represent works that otherwise do not exist. The erased writing becomes slightly visible with age, but is still difficult for scholars to read. In the 19th century, it was determined that applying some chemical elements of the ink that had been removed back onto the page could enhance the writing. A number of reagents were developed to enhance the erased text. Unfortunately, over the following years, these added reagents darkened and made the erased text less visible to later scholars. Eventually, this practice was discontinued.

In the early 1900s, scholars were learning that various optical filters could help improve visibility. One scholar, Father Raphael Kögel, discovered that ultraviolet light enhances the visibility of the erased writing.¹ Under ultraviolet illumination, the parchment would fluoresce, i.e. emit visible light, but the residual ink stains in the erased writing would inhibit that fluorescence, making the erased text darker in comparison to its surroundings and therefore more visible. Since that ground-breaking discovery, several more technological advances have been developed that have increased the options available to reveal the erased writing.

Advances in remote sensing, i.e. the study of the earth from satellites in earth orbit, have provided several tools for analyzing satellite multispectral image data. Multispectral images are the same as everyday images, except that each image is made with the light from a very narrow spectral region, i.e., each image is made from a single colour. X-ray fluorescence (XRF) also has revealed erased writing, especially writing that is covered by optically opaque material.² XRF is used today to identify individual elements of a material. An XRF image of the locations of concentrations of iron or calcium can reveal erased inks where traces of those materials from the ink remain in the parchment.

In this paper, recent optical methods and software algorithms will be described that have been developed to reveal erased writing. The optical methods were developed by the EMEL (Early Manuscripts Electronic Library) team, and the software algorithms were developed by the author. The optical imaging equipment is available commercially, while the software described here is freely available at <http://r-chive.com/software>.

MULTISPECTRAL IMAGING

Light interacts with the parchment, and the inks on it, in four distinct ways—reflectance, transmission, fluorescence, and angle-of-incidence.

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* The author wishes to acknowledge the contributions to this work from a team of scientists and scholars. Over the last decade, these efforts have been organized by Michael Phelps, the director of the Early Manuscripts Electronic Library (EMEL). At various times, the team has included Ken Boydston from MegaVision, Damianos Kasotakis from EMEL, Ivan Shevchuk from University of Hamburg, and Roger Easton, Jr. from Rochester Institute of Technology. In particular, over many years, Roger Easton, Jr. has contributed many helpful suggestions as these algorithms were being developed. Early efforts at text recovery were supported by William Noel from University of Pennsylvania, originally from the Walters Art Museum, and funded by the anonymous Owner of the Archimedes Palimpsest. The efforts on the Sinai Palimpsests Project were funded by the Arcadia Fund. The efforts on the Petermann manuscript were funded by the German Research Foundation (DFG) [project no. STU 469/1-1].

¹ Kögel, Die Palimpsestphotographie, and Kögel, *Die Palimpsestphotographie*.

² Bergmann and Knox, Pseudo-color enhanced x-ray fluorescence imaging.

What is light? By some definitions, light is electromagnetic radiation that we can see with our eyes. This is also called visible light. The electromagnetic spectrum just beyond the visible region is called ultraviolet, for radiation with a shorter wavelength than blue light, the shortest wavelength of the visible region. It is called infrared for wavelengths longer than red light, the longest visible wavelength. Your eyes cannot see the ultraviolet, or the infrared illumination, but the sensor in the camera can. The parchment and inks also interact with these wavelengths, so these are important regions of the spectrum, even though, to your eye, nothing appears to be happening when the manuscript is illuminated by invisible light.

Reflectance is the most common way that we think of light interacting with a surface. Light is incident on the surface and it is reflected off the surface towards the observer, i.e. either a person or a camera. The colour of the light that is reflected depends on the material. If the material appears to you to be 'red', it is because the red light incident on the surface is reflected. All other wavelengths are absorbed. For example, green and blue light that is incident on a 'red' surface would be absorbed in the material and would not be seen. It is reflectance that gives rise to what we think of as the 'colour' of the material. Reflectance images can be used to distinguish between materials of different colours.

The light that does not reflect from the surface will enter the parchment. Some of the light will be absorbed by the parchment. In addition, some will be scattered around within the parchment. Some of the scattered light will make its way back to the front surface and be emitted from the parchment close to where it entered. Other scattered light will make its way through the parchment and come out of the back surface of the parchment. This latter light is called transmitted light, or transmittance.

To be transmitted through the parchment, the light has to avoid being absorbed or being scattered too many times. Shorter wavelengths, ultraviolet and blue light, are scattered a lot, so these wavelengths end up transmitting very little light. Most of it is scattered and absorbed. The longer wavelengths are scattered less and are the main component of the transmittance. As a result, infrared light is best for capturing transmission images.

Transmitted light is very good for detecting small differences in thickness of the parchment. Any differences in thickness of the parchment will show up as variations of brightness in the transmission images. Thinner regions of the parchment will scatter the light less, allowing more light to be transmitted in that region. This turns out to be very helpful in detecting characters that have eroded the parchment, leaving small cavities in the parchment that take the shape of the missing characters.

Fluorescence is a completely different process. For reflectance, if the parchment is illuminated with light of a specific wavelength, the reflected light consists of light of that exact wavelength. Similarly, with transmittance, the transmitted light is the same wavelength as the incident light. This is not true of fluorescence. Fluorescence is most useful in enhancing stains left in the parchment from erased iron gall ink.

Fluorescence is the process of light being absorbed by the material and then re-emitted at a different, i.e. a longer, wavelength. The shorter the wavelength of the light, the more energy it contains. When a short wavelength is absorbed, it can dislodge an electron in an atom. This electron hole needs to be refilled, and an electron from a higher orbit in the atom takes its place. In jumping to a lower orbit, this second electron gives up energy by releasing a photon of light. Some energy is lost in this process, so the energy of the emitted photon is less than the original incident photon, and therefore the wavelength is longer.

For fluorescence to occur, the incident light has to have enough energy to dislodge an electron. This requires very short wavelengths, either ultraviolet or very blue light. Other wavelengths of light, green through infrared, do not have the energy to cause fluorescence. The re-emitted light, the fluorescence, is at a longer wavelength. Most often this is blue light, but sometimes it can be green, red, or even, in rare cases, infrared light. In any case, for all cases of fluorescence, the light that comes back to the camera (the fluorescence) is not the same wavelength as the incident light.

As a result, when the parchment is illuminated with ultraviolet light, some ultraviolet light is reflected to the camera, and some fluorescence, likely some form of visible light, is also emitted in the direction of the camera. The image of the parchment, therefore, has both reflectance and fluorescence light in the image. To separate out the two responses of the parchment to the ultraviolet light, filters are placed in front of the camera to filter out one light or the other, so that all of the light can be seen individually. For example, a filter that only passes ultraviolet light would make an image of only the reflected ultraviolet light. A filter that passes only blue light would image the blue fluorescence. A filter that passes only green light would image the green fluorescence, etc. As a consequence, fluorescence images require filters to capture images at specific wavelengths. All other

image types—reflectance, transmission, and angle-of-incidence—do not require filters, because in those cases illuminating with light of a single colour produces images of the same, single colour.

The angle of the reflected light depends on the surface structure. A ‘diffuse’ surface is one that scatters the reflected light in all directions. As a result, a diffuse surface can be seen no matter what the angle of incidence of the illumination. A ‘specular’ surface is a very smooth surface. The angle of the reflected light, for a specular surface, depends heavily on the angle of the incident light, in relationship to the direction of the surface itself. An example of a specular reflection is a ‘glint’—that is, a small, bright, and direct reflection of the source of light in the direction of the observer. Move the observer or the light source by a small amount, and the glint will either move slightly or disappear.

The last type of optical image that we take is called a ‘raking’ image. It is called this because the illumination is incident on the parchment at a raking angle, i.e. a very shallow angle with respect to the surface. The light source is located a short distance above the surface, about ten or twenty degrees above the plane of the surface. At this angle, the light casts shadows on the surface due to the bumps and irregularities of the surface. These images allow the scholar to see not only irregularities of the surface, but also indentations, such as rulings and pinpricks. These images can help analyze how the manuscript was constructed.

IMAGING SYSTEM

To capture multispectral images of a manuscript, our team uses the commercially available EV™ imaging system³ from MegaVision,⁴ shown in Figure 1. The system consists of a high-resolution 50 megapixel, panchromatic camera, with panels of LED lights of different individual colours, diffusers for uniform illumination, a light sheet for transmission imaging, and LED strips for shallow-angle (raking) illumination.

The panchromatic camera will record light with a range of wavelengths from 365 nm (ultraviolet), through the visible region (400–700 nm), and into the infrared (700–1050 nm). There are no filters on the camera sensor, so whatever light that falls on it in its sensitivity range (365–1050 nm) will be recorded in the output image. It is the responsibility of the camera operator to see that only the desired wavelengths of light are entering the camera during the exposure.



Fig. 1: The EV™ MegaVision Cultural Heritage Imaging System in use at the Staatsbibliothek zu Berlin. Dale Stewart adjusts the manuscript, while Ivan Shevchuk operates the camera. The LED panels illuminate the manuscript with one colour at a time in a series of several exposures under control of the computer (© Keith Knox)

³ Christens-Barry *et al.*, Camera System for multispectral imaging, 2–5.

⁴ <https://mega-vision.com/> (accessed 01.07.2023).

As described earlier, for reflection, transmission, and raking images, the wavelength of the incident light is the wavelength of the response. For fluorescence imaging, filters in front of the camera, in a filter wheel, are used to choose the specific wavelengths of the fluorescence to be studied.

The parchment leaf to be imaged is placed on the light sheet ('transmissive light source'). This is a translucent piece of plastic, in which light from three wavelengths, 580 nm (yellow), 735 nm (infrared), and 940 nm (infrared), is fed into the edges of the sheet. The light transmits through the sheet and radiates out of the sheet under the leaf, sending light upward, through the leaf and towards the camera above. Because these are longer wavelengths, the light easily transmits through the leaf.

The strips of raking lights, seen in Figure 1, contain two wavelengths, 450 nm (blue), and 940 nm (infrared). Since iron gall ink tends to fade away in infrared light,⁵ the two wavelengths illuminate the topography with one type of light that exhibits legible writing, and another type of light that suppresses legible writing.

IMAGE PROCESSING

The process of manipulating digital images to enhance the desired details and to suppress the undesired details is called image processing. This is possible only if the information is present in the captured image data. Often the desired information is present, but it is in brightness regions that are not visible to the human eye. The goal of image processing is to find the desired information and to move it into brightness regions that the eye can see.

An image is a structured pattern of light, consisting of bright and dark regions, so that when they fall on the retina of the eye, the brain can interpret the original structure. A digital image is related to the original image, but is something different. A digital image is created when that same structured light pattern falls upon the camera's digital sensor. This sensor consists of a rectangular array of small detectors, called pixels (for 'picture elements'). Each detector element is sensitive to the light falling upon it. As the light is absorbed by the detector element, a charge builds up that is proportional to the amount of light falling upon it. The more light it sees, the more charge is stored in that detector element. This charge then passes through an analog-to-digital converter that converts the amount of charge to an integer number. The larger the number, the more charge was stored, and the more light fell upon that detector element. These numbers are read out of the camera and stored in a file in the computer in the same arrangement as the detector elements in the camera sensor. This array of numbers represents the amount of light that was seen by the camera sensor in the original image.

What can you do with a digital image? It is just an array of numbers. You cannot see an array of numbers as anything meaningful. To see the image that the digital array represents, you have to convert that array of numbers into an array of bright and dark areas on a display or a printer. To do that, you take the array and create a display with the amount of light displayed to be proportional to the numbers in the array. When you look at the newly-created image on a computer display, you now see the original image that was captured by the camera.

Here is where image processing enters. If you manipulate the numbers in the digital image to make some details brighter and other details darker, you can emphasize some features over others in the output display of the processed image. The method of identifying the desired features and making them more visible to the eye is what is called an image processing software algorithm. After those features are emphasized in the digital image, they can then be viewed by converting the digital image into an image on your computer display.

Fortunately, there are many available software programs to display or view a digital image on a computer display, so those programs do not need to be created. To make image processing algorithms and software to process the multispectral data of a manuscript leaf, all that is needed is 1) an understanding of how the image was captured, i.e. what the digital numbers represent in terms of the original images, and 2) a knowledge of how to identify, extract, and make visible the desired features in the original images. That is the subject of the rest of this paper.

STAINS FROM ERASED IRON GALL INK

Iron gall ink is made using tannic acid. The resultant tannin compounds in the ink soak into the parchment. When the particulates of the iron gall ink are removed by erasing the ink, the stains from the tannins remain

⁵ Rabin *et al.*, Identification and classification.

in the parchment. These stains darken with time, making them more visible, but still hard to read. Under ultraviolet illumination, the parchment fluoresces in the visible region, i.e. in blue, green, or red light, making the parchment very bright. On the other hand, the tannins in the parchment inhibit the fluorescence in the parchment.⁶ As a result, located next to the fluorescing parchment, the erased characters appear darker under ultraviolet illumination.

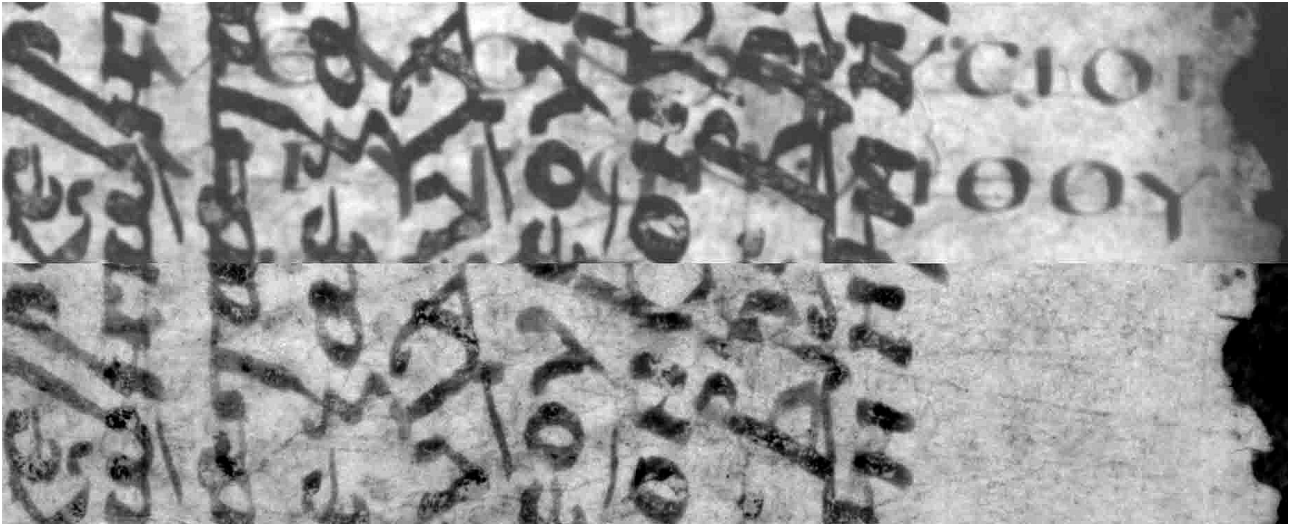


Fig. 2: Two images made with 365 nm ultraviolet light (top image), and 940 nm infrared light (bottom image). Note that the erased writing (horizontal) is legible in ultraviolet illumination and disappears in the infrared. This is a segment of the manuscript Sin. gr. NF MG 99 (© St. Catherine's Monastery, Sinai, Egypt)

The two images in Figure 2 show the response of the parchment side under ultraviolet illumination (365 nm), and under infrared illumination (940 nm). Note that the overwriting is dark under both illuminations, but the erased writing is dark in the ultraviolet image and is not visible in the infrared image.

The different responses, of the erased writing and the overwriting, can be used to enhance the erased writing for the scholar to read. In Figure 3, the top segment is a region of the side illuminated in natural light. This is how the leaf looks to the human eye in colour. The erased writing is reasonably legible in the margin on the right. Hints of the erased writing can be seen in the region of the overwriting, but, in general, the erased writing is indistinct and hard to read. Often, a simple combination of two of the spectral images, an ultraviolet image with a visible or infrared image (see Fig. 2), can be made either to suppress the overwriting, or to enhance the erased writing.

In a 'pseudocolour' image, the two images are combined in a manner which enhances the erased writing.⁷ The result is a colour image in which the overwriting is a neutral gray or black, and the erased writing is coloured—in this case, coloured red (see the bottom part of Fig. 3). The colour of the erased writing makes it stand out from the overwriting and therefore easier to read. The contrast of the erased red writing in the pseudocolour image will not seem as dramatic to a red-green colourblind person as it does to the rest of the population.

Alternatively, the two images can be combined in a different manner to suppress the overwriting, thereby enhancing the erased writing in a monochrome image. In the middle part of Figure 3 is a 'sharpie',⁸ which is the difference of the ultraviolet and visible images. This processed image tends to suppress the overwriting, making it look like the parchment. This suppression of the overwriting makes the contrast of the erased writing dominant. Depending on the condition of the parchment or the writing, or the colour vision of the observer, the erased writing may be more visible either in the pseudocolour or the sharpie, hence we produce both.

⁶ Rabin *et al.*, Initial inspection of reagent damage.

⁷ Easton *et al.*, Multispectral imaging of the Archimedes Palimpsest, 2.

⁸ Named after [https://en.wikipedia.org/wiki/Robert_Sharples_\(classicist\)](https://en.wikipedia.org/wiki/Robert_Sharples_(classicist)) (accessed 01.07.2023), who preferred this image type.

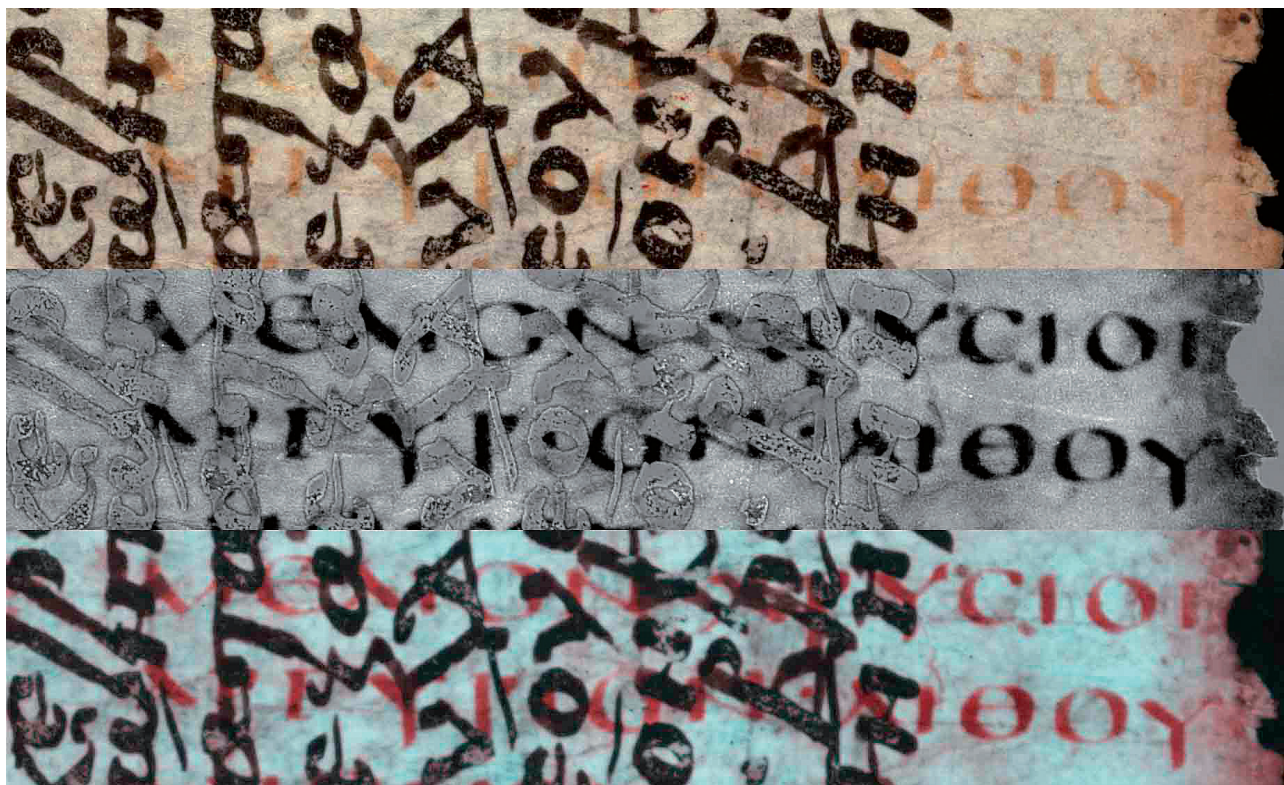


Fig. 3: Three processed images of the segment of the manuscript Sin. gr. NF MG 99, ff. 3v–4r. The top image represents the appearance in natural light. The middle image is a ‘sharpie’, while the bottom is a ‘pseudocolour’. The erased writing is enhanced in the bottom two images, by suppressing the overwriting in the sharpie and inserting colour in the pseudocolour
 (© St. Catherine’s Monastery, Sinai, Egypt)

The combination of the two images in Figure 2, into either a pseudocolour image or a difference image (sharpie), is accomplished only after pre-processing both images. Directly out of the camera, the numbers in the two images may have completely different dynamic ranges, i.e. a corresponding white spot in each image may be represented by drastically different numbers, due to differences in exposure or to different detector sensitivities. If the ultraviolet and infrared images are inserted into a colour image, and the values of a white spot on the two images have different values, then that spot in the colour image will not be white, but instead will take on the colour of the image with the larger value. To make neutral colours be actually neutral in colour, the values of the two images need to be adjusted, so that corresponding white areas have comparable values.

Adjustments to the dynamic ranges of the two images are made with a ‘normalization’ algorithm.⁹ This process slides a small window across each image. This window may be as large as 500×500 pixels for an $8,000 \times 6,000$ pixel image. At each location of the sliding window, the adjustment to the pixel in the centre of the window is determined by measuring the statistics of the data within the window at that location—namely, the mean and the standard deviation. The contrast of the centre pixel is adjusted by shifting the mean value from the measured mean to mid-gray, then stretching the contrast so that the minimum (black) and the maximum (white) values are each 3 standard deviations away from the mid-gray value.

This normalization process can produce problems around high-contrast regions in the data. When the sliding window initially encounters a high-contrast character, such a character of the overwriting, the standard deviation significantly increases. With a larger standard deviation in the data, a smaller contrast adjustment is called for. This means that regions around high-contrast characters appear to have a ‘veil’ of low-contrast enhancement around them. To counter this effect, a ‘no-veil’ normalization was developed that uses a mask that is aligned with the high-contrast detail in the image. Image values defined by the mask are not used in calculating the standard deviation, hence the contrast adjustment does not change within regions of the high-contrast data,

⁹ Knox, *Enhancement of overwritten text*, 5.

thereby eliminating the veil. The mask is determined using a sliding window, adaptive version of the Otsu method of binarization.

After this 'normalization' process, the two images can now be combined together. Points that appear to have the same visibility will also have similar values in the normalized images. For example, the parchment in the two pre-processed images will have similar values, as will the overwriting. As a result, in the difference image (sharpie), the parchment and the overwriting will have similar values, and the overwriting will disappear into the parchment. The erased writing, on the other hand, will have significantly different values in the two normalized images, because the erased writing is visible in one and invisible in the other. In the difference image, this large difference shows up as a high contrast character, easily seen against the suppressed overwriting.

For the pseudocolour image, the normalized ultraviolet image is inserted in the green and blue colour separations of the pseudocolour image, while the normalized infrared image is inserted into the red separation. Since the overwriting, visible in both images, has similar values in both, it shows up in the pseudocolour image as a neutral gray, or a black colour. The erased writing, on the other hand, is bright in the red separation, and dark in the other two separations, making it a bright red colour. In this way, the high-contrast difference of the erased writing is turned into a strong colour difference in the pseudocolour image.

These two methods, the pseudocolour and sharpie, are simple to implement and quick to apply. For many cases, these two methods provide sufficient information for the scholar to read the erased writing. As long as the erased writing consists of iron gall stains in parchment, these two methods will give a good rendition of the erased writing.

ERODED PARCHMENT

The chemicals contained in iron gall ink are harsh and can erode the parchment. When they do, they can remove the residual stains from the erased ink, and a small amount of the parchment that held them. As a result, the parchment is thinner where the erased characters were located. Without the stains, the thinner parchment does not inhibit the fluorescence, so the characters are not darker under ultraviolet illumination. Because the parchment is thinner, though, there is a slightly smaller fluorescence response, due to the fact that there is less scattering of the fluorescence from the nearby parchment into that region. This results in ghost traces of the characters in the pseudocolour images. These traces look similar to the response of the writing that shows through from the other side of the leaf. As a result, the eroded characters do not show up in the pseudocolour as erased writing. Ultraviolet illumination does not help reveal the erased writing when the character stains have been eroded away.

Interestingly, although the regions of thinner parchment do not show up well in ultraviolet illumination, they show up beautifully in infrared transmission. This was discovered accidentally by Michael Phelps in the beginning stages of the Sinai Palimpsests Project in 2009. Holding a leaf up to the light from a lamp across the room revealed white characters that could not be seen by the eye in normal reflection. This discovery led to the development of the transmission ratio algorithm.

Infrared light is the light that travels easiest through parchment, so when infrared light is shone through the parchment, these thinner eroded character regions are much brighter than the surrounding regions. Because the thinner eroded regions scatter less light, they allow more light through. The erased writing then can be seen as white characters on a darker background. The front surface overwriting also shows up in the transmission image. To suppress those characters, the transmission image is divided by the front surface, infrared reflectance image (940 nm), which contains mostly just the unwanted overwriting. This suppresses the characters on the front surface, making the erased characters more legible.

Remember that digital images are just arrays of numbers. As such, one can divide one set of numbers by the other. When the numbers are of comparable value (equal brightness), they tend to cancel in the ratio. When the denominator value is smaller (darker) than the numerator, it makes the ratio larger (brighter), and vice versa. Taking a ratio of two images is a way of suppressing a feature that is of comparable value in the two images.

When two images are divided, the resulting ratio is centred around unity with many of the values being close to unity. This is not a range of values that easily translates to a visible range of values. To get the resulting values in range, a 'normalization' of the ratio is performed. This process contrast stretches the result, making the details more visible.

The parchment leaf consists of two sides, the hair side and the flesh side. By its nature, the hair side is more resilient to the tannic compounds than the flesh side. As a result, it is the flesh side that is more susceptible to erosion from the ink. That means when light is transmitted through the parchment, the only white characters that are seen are from the flesh side of the leaf. Since the characters on the hair side typically are not eroded, those stains remain and can be enhanced with ultraviolet illumination and the pseudocolour or sharpie processing.

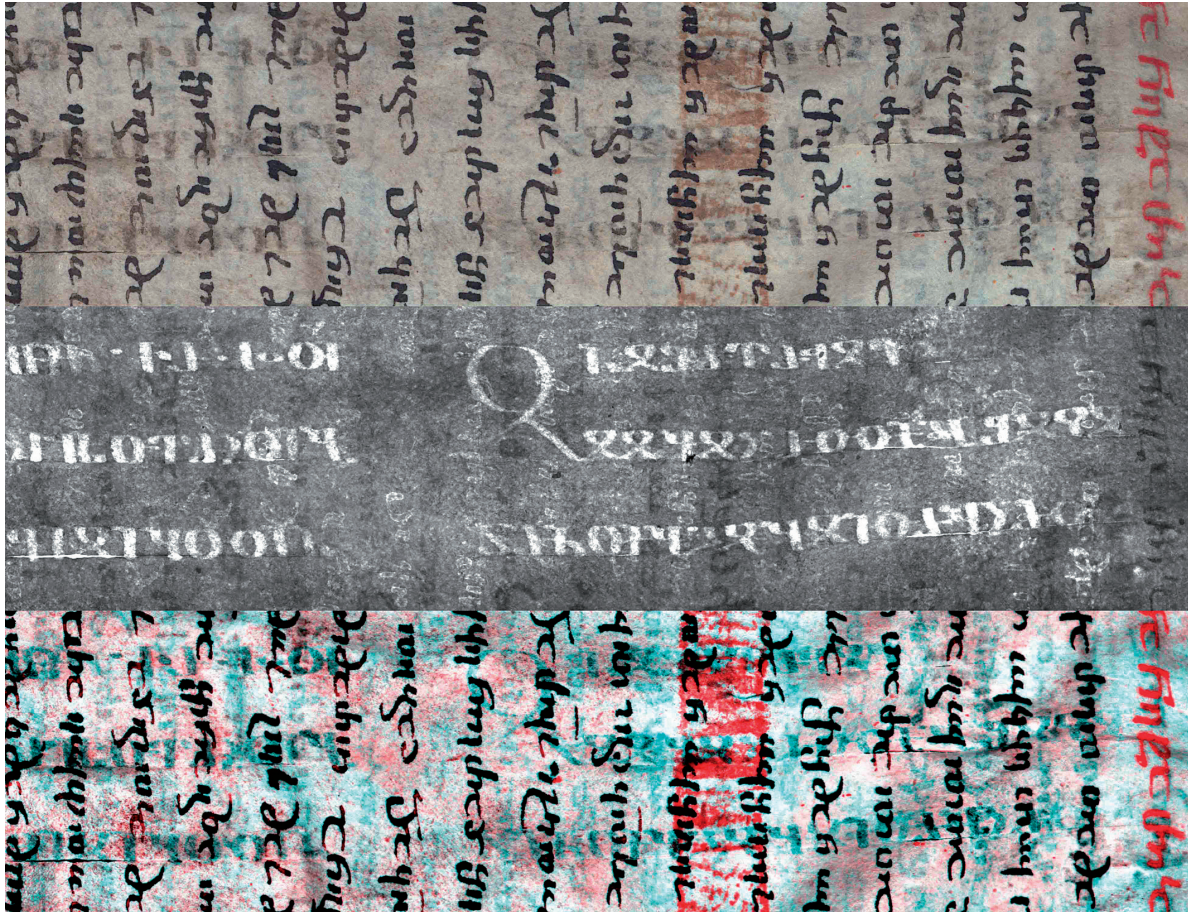


Fig. 4: The transmission ratio algorithm is valuable for eroded images, as in this segment of Sin. geo. NF 13, f. 59r. The natural light image (top) shows only smudges for the erased writing. The transmission ratio image (middle) of exactly the same region reveals the erased characters. The pseudocolour image (bottom) only shows coloured smudges. Ultraviolet illumination did not help here
(© St. Catherine's Monastery, Sinai, Egypt)

A striking example of a transmission ratio image is shown in Figure 4. In the upper segment, hints of the erased writing are seen in horizontal lines of smudges. The bottom segment shows the pseudocolour image, which does not bring out the erased writing, but instead shows a coloured set of smudged characters.

In the middle segment is the transmission ratio image. In this image, the erased writing is clear and crisp, and the overwriting has been almost completely suppressed. Although the middle image appears dramatically different from the other two images in the figure, it is indeed the exact same region of the same leaf. Not all transmission ratio images are this good. Note that in some cases on this leaf, the bright characters are formed even in places where there is significant overwriting. This suggests to the viewer that perhaps the erosion had occurred before the leaf was erased and overwritten, otherwise the overwriting would also have fallen off when the erosion occurred.

When significant erosion of the text characters has occurred, typically on the flesh side of the leaf, the transmission ratio technique can be invaluable. When no erosion has occurred, normal ultraviolet illumination and processing work best. The work on the image of this leaf was done in consultation with Jost Gippert, as part of the Sinai Palimpsests Project.

RULING LINES, PINPRICKS, AND COCKLED SURFACES

Indentations in the surface of the parchment can indicate features of the manuscript that otherwise do not easily appear to the eye. At times, people have tried to use illumination at very shallow angles (raking light) to reveal textual indentations, but that has not been very successful. On the other hand, raking light images are successful at showing the patterns of cockling of the parchment, ruling lines, and pinpricks.

Special raking lights are positioned to the left and right sides of the sheet, so that the light they cast hits the parchment at a very shallow angle, just grazing across the surface. One of the raking light strips can be seen in Figure 1, just behind the person adjusting the manuscript. These light strips emit wavelengths in the blue and infrared regions of the spectrum. Under infrared illumination, the contrast of the writing is reduced, so that the surface is better revealed.

A processed raking image is created by taking the difference of the two infrared raking images. These two images show the overwriting clearly and at similar gray levels. By taking the difference, the text is significantly suppressed. On the other hand, the raking image does show small surface variations, such as the ruling lines and pinpricks. It also shows the wrinkles of the cockled surface distinctly. Because the indentations appear slightly shifted in opposite directions, when viewed with light from the two opposites sides, the shadows of the indentations do not cancel in the difference image, but rather are enhanced. Features such as ruling lines do not always show up, but if they are visible in a raking image, then that gives evidence of a layer of erased writing.

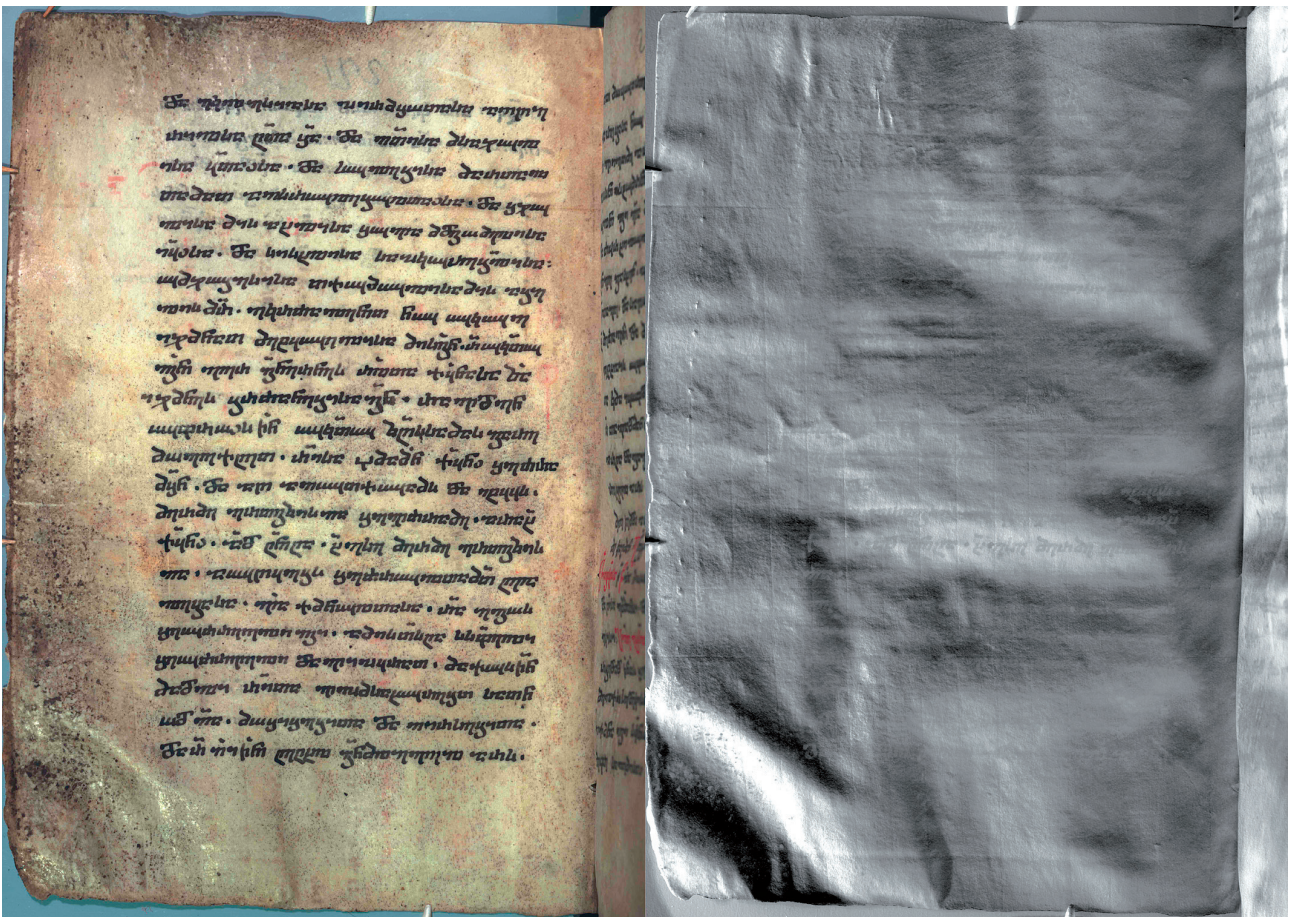


Fig. 5: The raking light image (right) of Sin. geo. 10, f. 221v, reveals the ruling lines and pinpricks that are not visible in the natural light image (left)

(© St. Catherine's Monastery, Sinai, Egypt)

Figure 5 shows a natural light image of a folio, along with its corresponding raking image. The natural light image has been illuminated with diffuse light and it shows little indication of surface variations. On the other hand, the raking image shows clear indications of pinpricks along the left margin and two sets of ruling lines,

one set oriented vertically and the other oriented horizontally. This second set of ruling lines can be used to indicate where erased characters might be expected on the folio.

FLUORESCING CHARACTERS

Usually, the residual stains of the ink do not fluoresce. Instead, they typically suppress fluorescence of the parchment, making the characters darker. In some rare cases, we have seen erased characters that appear to fluoresce. We do not know for certain why this happens. It may be that it is the parchment in the regions of the erased characters that fluoresces. Whatever the case, the result is white characters in a filtered fluorescence image. In the case shown in Figure 6, the top two segments are two different images captured under ultraviolet illumination. The upper segment was taken with a blue filter, while the middle segment was taken with a red filter. Note that the erased characters are darker than the parchment seen through the blue filter and are brighter than the parchment seen through the red filter. They were also brighter than the parchment when seen through the green filter. Because they are brighter in the green and the red, the erased characters are fluorescing in a colour that is more yellow than the parchment fluorescence, i.e. a colour fluorescence image would show yellow erased writing.

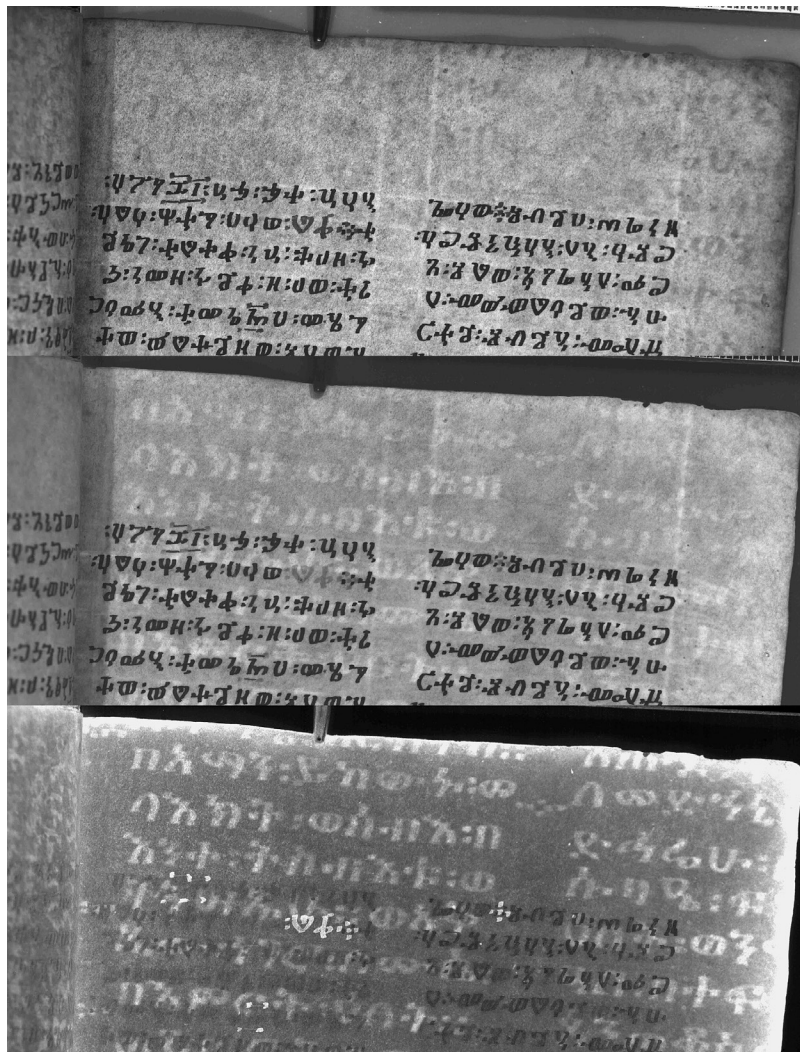


Fig. 6: A ratio of fluorescence images can enhance the erased writing, in the case where the erased writing fluoresces. The blue-filtered fluorescence image (top) shows characters darker than the parchment, while in the red-filtered fluorescence image (middle) the erased characters are lighter. Combining those two images in a ratio (bottom) significantly enhances the erased writing. This is a segment of

Petermann II, Nachtr. 24, f. 94, an Ethiopic manuscript

(© Staatsbibliothek zu Berlin – Preussischer Kulturbesitz, Orientabteilung)

The fluorescence of the erased writing, visible in the middle segment in Figure 6, is not usual, but it can be utilized to enhance the erased characters. To enhance these characters the fluorescence ratio algorithm was developed.

The bottom image shows the ratio of the red-filtered UV image by the blue-filtered UV image. The dark characters correspond to low digital values. By dividing by a low number, one increases the value being divided. As a result, the white characters of the red-filtered image, when divided by the dark characters of the blue-filtered image, become even brighter. To enhance the features in the ratio image, the normalization algorithm is applied to stretch the contrast of the values, making them more visible.

The result, a fluorescence ratio image, is shown in the bottom segment. The erased characters are clearly visible in this image. When compared with the two filter fluorescence images, the fluorescence ratio shows more of the erased writing than either. This work was done together with Ted Erho and Loren Stuckenbruck on an Ethiopic manuscript at Staatsbibliothek zu Berlin.

CONCLUSIONS

The image processing techniques described in this paper have been developed by the author over the last two decades. The original pseudocolour and sharpie methods were developed as part of the Archimedes Palimpsest Project during the first decade of this century. The transmission ratio and the raking light algorithms were developed as part of the Sinai Palimpsests Project in the second decade. Lastly, the fluorescence ratio algorithm was developed in the last few years, to read the Petermann II Nachtrag 24, Ethiopic palimpsest.

In the author's opinion, the development of image processing techniques to reveal erased text in palimpsests or damaged manuscripts is still in its infancy. Every new project introduces new conditions of parchment, inks, or environmental damage that require different approaches to recover erased or damaged writing. As these new algorithms are developed, it is important to understand the underlying physics of the degradation to see how to construct the algorithm that will reverse the damage and reveal the missing writing. This understanding will also help others to determine when a specific tool might be applicable to another manuscript.

The software that implements these algorithms was originally written in the C-language to be run on UNIX platforms. This software was reimplemented in Java to make it available for people to use on other computer platforms, such as macOS and Windows. In addition, a graphical user interface was added to make the software easier to use and to understand. This software, called Hoku, is available on <http://t-chive.com/software>.

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