

LED Imaging of the Archimedes Palimpsest

This section of the website is adapted from a technical report by William A. Christens Barry, Ph.D. on the experimental LED Imaging of the Archimedes Palimpsest.

Introduction

Early phases of the imaging project examined the potential for enhancement of the Archimedean text through the use of narrowband multispectral imaging techniques. This work involved the use of narrow band filters in the light path to allow a series of narrowband images to be collected. The RIT-Xerox team employed a computer-driven liquid crystal tunable filter (LCTF), under computer control, to achieve images in very narrow ($\sim 10\text{nm}$) wavelength bands spanning the visible spectrum (roughly $400\text{ nm} - 700\text{ nm}$).

Analysis of these data resulted in several findings that guided subsequent imaging efforts. It was noted that:

- (i) High spectral resolution greatly aided the use of traditional spectral domain image analysis techniques, such as principal components analysis (PCA) and variants.
- (ii) The introduction of filters into the optical path reduced the spatial resolution of the acquired images. The LCTF, a sophisticated device with active optical elements, resulted in a marked reduction in resolution while the simple glass filters only modestly reduced resolution.

In total, it was recognized that this approach alone could not produce the optimal combination of high spectral and high spatial resolution. It was additionally recognized that the design of an efficient production imaging effort, in which the scholars placed high value on visually readable representations of the images rather than on strictly numerical results that were more difficult to comprehend, would have to depend initially on a simpler, speedier imaging and processing approach. Guided by the needs of the scholars, the imaging team, conservators, and project management jointly devised a simpler approach that required far fewer images to produce results that the scholars felt eager to work with. This approach, employed in the “production imaging of the Archimedes Palimpsest, and referred to as the “pseudocolor” technique, utilized an RGB color camera (Kodak DCS660 and later the Kodak DCS760) to collect sets of three images of each region of the palimpsest. Images collected in the pseudocolor approach used ultraviolet

(UV; 365 nm) from a single light source, and broadband white illumination from a Xenon strobe flashlamp and from a pair of tungsten incandescent bulbs. This methodology worked well, allowing up to fifteen bifolia to be imaged during each subsequent imaging session and producing results that have allowed the scholars to improve their reading of the Archimedean text.

Yet, it was recognized that it would be worthwhile to continue to examine how the multispectral approach could be modified or improved to allow its use to augment the pseudocolor imaging that was adopted for production imaging. Two principal thoughts were central to our thinking:

- (i) The use of broadband white light to illuminate the manuscript leaves, followed by filtering of this light during the acquisition of narrowband images, meant that far more light was incident on the leaves than was needed for the acquisition of any single narrowband image. This conflicted with the conservation goal of minimizing the light dose delivered to the manuscript.
- (ii) The placement of filters in the optical system between the manuscript and the camera (as was done by both teams) degraded image spatial resolution.

During our planning for production imaging, we recognized that both of these objections could be overcome by the use of filters in the illumination path, rather than the imaging path. Placement of filters between the light source and the manuscript ensures that only the narrow band of wavelengths to be acquired by the camera would strike the leaves, thereby reducing the light dose. Upstream filter placement also eliminates the spatial degradation to the image that occurs when any optical component is placed on the imaging side of the system.

Based on this realization, a revised multispectral system was used in several later imaging sessions. This work utilized a high intensity (150 W) tungsten illuminator and two banks of narrow bandpass (~ 50 nm) glass filters, together with optical fiber light guides, to achieve narrowband illumination without filter components in the imaging system. A series of 50 nm bandwidth images was collected at 50 nm wavelength intervals (from 400 nm to 700 nm), at 800 nm and 900 nm, and a set of 25 nm bandwidth images were collected at 25 nm intervals (intermediate between the 50 nm interval images) through the use of “synthetic” 25 nm bandwidth filters generated by use of overlapping pairs of 50 nm bandwidth filters.

Results showed:

- (i) Excellent image spatial resolution, comparable with that obtained with the RGB color camera, could be collected using this “upstream” filtering.
- (ii) Images obtained using the “synthetic” 25 nm bandwidth filters were of little value, due to the greatly reduced signal-to-noise ratio (SNR) that obtained from the double filtration resulting from the use of two filters.
- (iii) The bandwidth of the single filters (~ 50 nm) was too great, and their number too few, to allow sufficient spectral resolution for numerical results to produce processed images that could greatly aid the scholars.
- (iv) Manual operation of the filter banks, coupled with the need to collect many more images, was far too slow to allow this technique to be used as a mainstream production technique.

During the April 2004 Archimedes Workshop, it was proposed that light emitting diode (LED) technology had advanced sufficiently that we could use a bank of narrowband LEDs to overcome several of the difficulties encountered in this approach:

- (i) LED sources with sufficient power (> 50 mW) and narrowband output (< 25 nm) were available in wavelengths throughout the visible spectrum.
- (ii) High switching speed (> 1 Mhz) of LEDs and the ease with which they can be placed under computer control would allow much more rapid image collection.

Following the symposium, it was decided that this approach would be implemented and used during the November 2004 imaging session. This report briefly describes that effort, shows some illustrative results and sketches some initial conclusions.

METHODS

A. Apparatus

Selection of wavelengths was governed by three factors: availability of LEDs; ease of drive electronics fabrication for a particular LED type; the imaging team's experience and findings from earlier imaging and production.

Luxeon V and Luxeon I LEDs (see Figure 1) have numerous optical advantages over devices made by other manufacturers. They have the added benefit that both types can be driven using identical circuitry. Other wavelengths could not be obtained from other manufacturers due to inadequate time for designing and fabricating the control and fiber coupling optics before the November 2004 imaging session. In consequence, the LED illuminator utilized the following wavelengths and devices:

<u>Center wavelength (nm)</u>	<u>Power (mW)</u>	<u>Color</u>	<u>Device type</u>
455	1000	deep blue	Luxeon V
470	1000	blue	Luxeon V
505	1000	cyan	Luxeon V
530	1000	green	Luxeon V
590	200	amber	Luxeon I
617	200	orange-red	Luxeon I
625	200	red	Luxeon I



Figure 1: Luxeon V high power LED. Light is emitted by the square active region at the center of the device. This LED emits 1 Watt of light at 470 nm.

Just prior to the imaging session, a wire bond failure killed output from one of the amber LEDs (590 nm). Because the LEDs at each wavelength must be used in pairs to achieve balanced lighting, this wavelength was not used during the November 2004 imaging session.

The assembled control board and LED-optical fiber assembly are shown in Figure 2. Two bundles of optical fibers were used; each bundle contains a single optical fiber from one LED of the pair at each wavelength (7 fibers per bundle). Each bundle used a single output coupler to ensure that each of the fibers produced a similar light distribution. Finally, each output coupler

include a film diffuser to remove any spatial fine structure from the output and ensure a relatively smooth, flat intensity distribution.

A LabJack U12 interface control board that mediates the control of the LED board by computer software is partially visible toward the upper left of the figure. The user interface of the simple LED control software is shown in Figure 3.

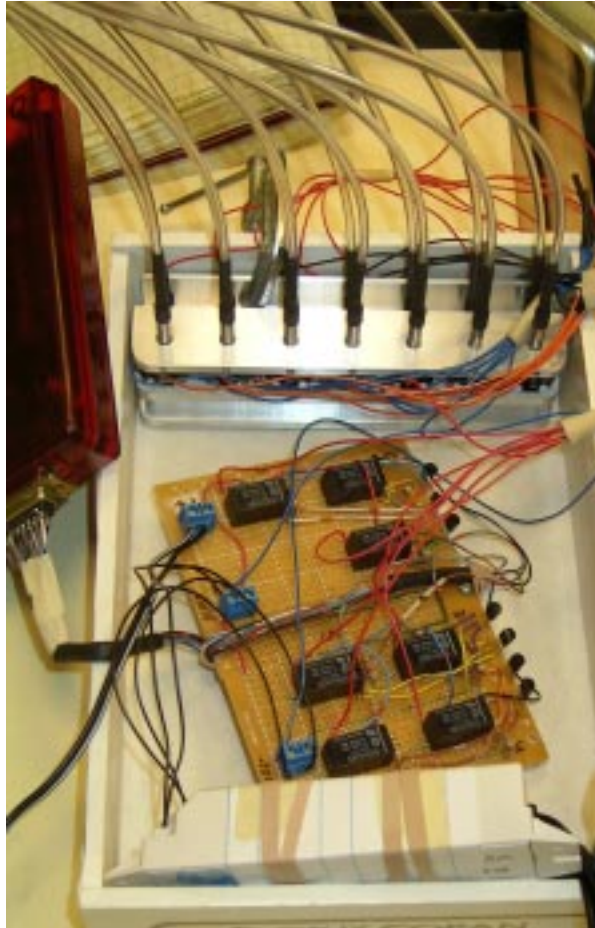


Figure 2: LED circuitry and optical fibers

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Figure 3: Photo of user control screen

B. Image acquisition

Spectra of the LED used during the imaging session are shown in Figure 4. Each device has a narrow spread of output wavelengths (typically less than 30 nm FWHM). While there is overlap in the output from the different wavelength LEDs, it is narrow compared to the transmission

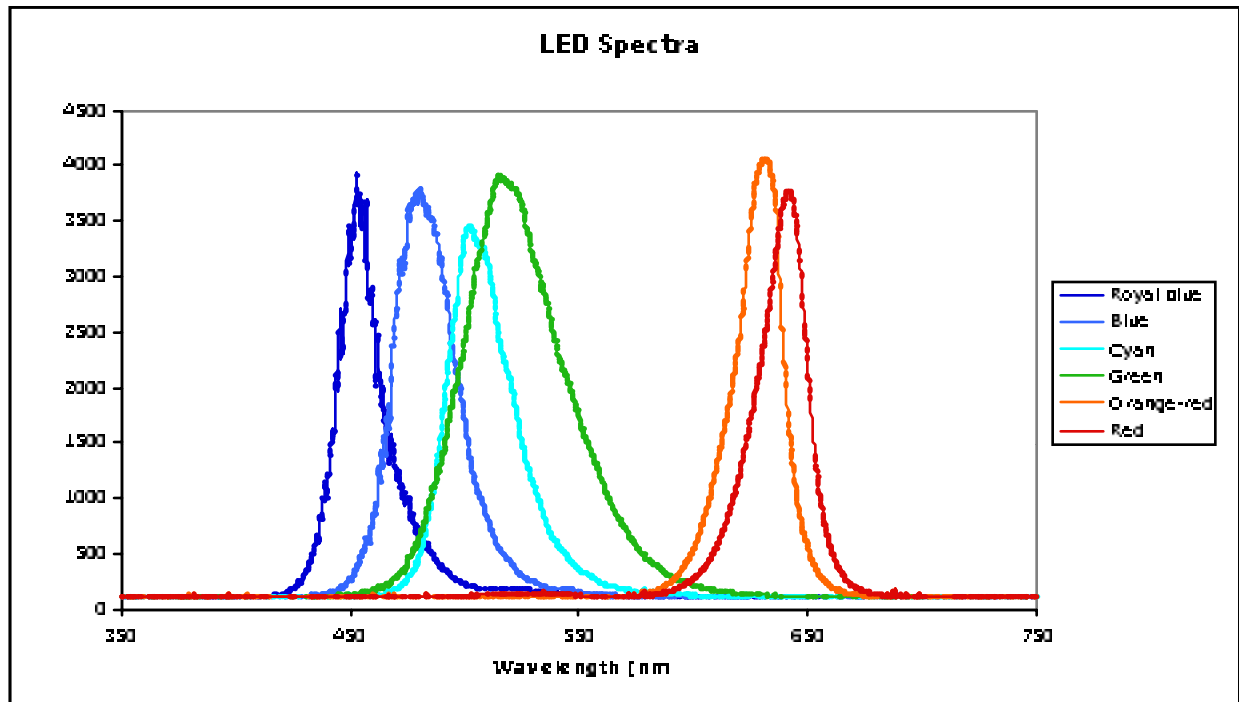


Figure 4: LED spectra

spectra of the Bayer mask used in the Kodak DCS 760 color camera. It is thus possible to more precisely control and attribute the color information used in processing, such as is done using the pseudocolor software.

Images were collected at each region of the palimpsest using LED illumination, the UV source (at 365 nm), and in the IR (at 700 nm and 800 nm) using the filtered tungsten source that had been built for earlier work. In this way a set of images spanning the spectrum from the UV, through the visible, and into the IR were collected and available for enhancement processing.

At each position, a series of different wavelength images was acquired, in order of increasing wavelength (UV $\rightarrow$ visible $\rightarrow$ IR). Standard exposure levels for the different wavelengths were established early in the November session. The exposure level was checked for each side of each leaf, and standard exposure levels were modified only when required for especially dark or highly reflective leaves. The position of the optical fibers and the illumination flatness and

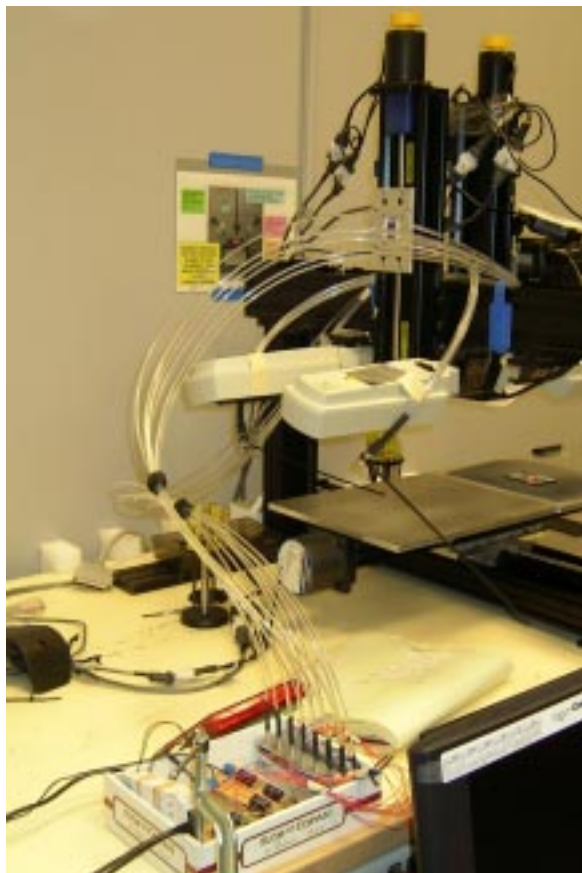


Figure 5: LED illuminator in imaging system

overlap were checked and adjusted each morning before images were acquired. Dark field and flat field images were acquired periodically for use in calibration procedures.

Because the Sensys monochrome camera has a 1536 x 1024 pixel layout, rather than the 3040 x 2008 pixel format of the DCS 760, each image covered one quarter of the area that the DCS 760 covered at equal resolution (approx. 625 dpi). Consequently, each side of a bifolium was imaged as a mosaic of 40 subregion images, or 4 times as many subregions as with the DCS 760 production camera.

RESULTS

A. Acquired images

In total, 7540 images were collected during 4 days of the imaging session. The six folios imaged using the LED illumination system were:

28V (singleton)	105V-110R (bifolium; one side)
1V (singleton)	76V-76R / 77V-76R (bifolium; both sides)
163R (singleton)	120V-121R (bifolium; one side)

B. Monochrome images from narrowband LED pairs

Single images from region 7 of folio 105V-110R that were obtained using narrowband LED and UV sources are shown for illustrative purposes in Figure 6 (these images were used to obtain the synthetic RGB and pseudocolor images of Figs. 7 and 8, respectively).



Figure 6. Sample monochrome images obtained (clockwise from top left) using 625 nm, 530 nm, and 365 nm fluorescence images, respectively.

C. Synthesis of RGB images from acquired narrowband LED images

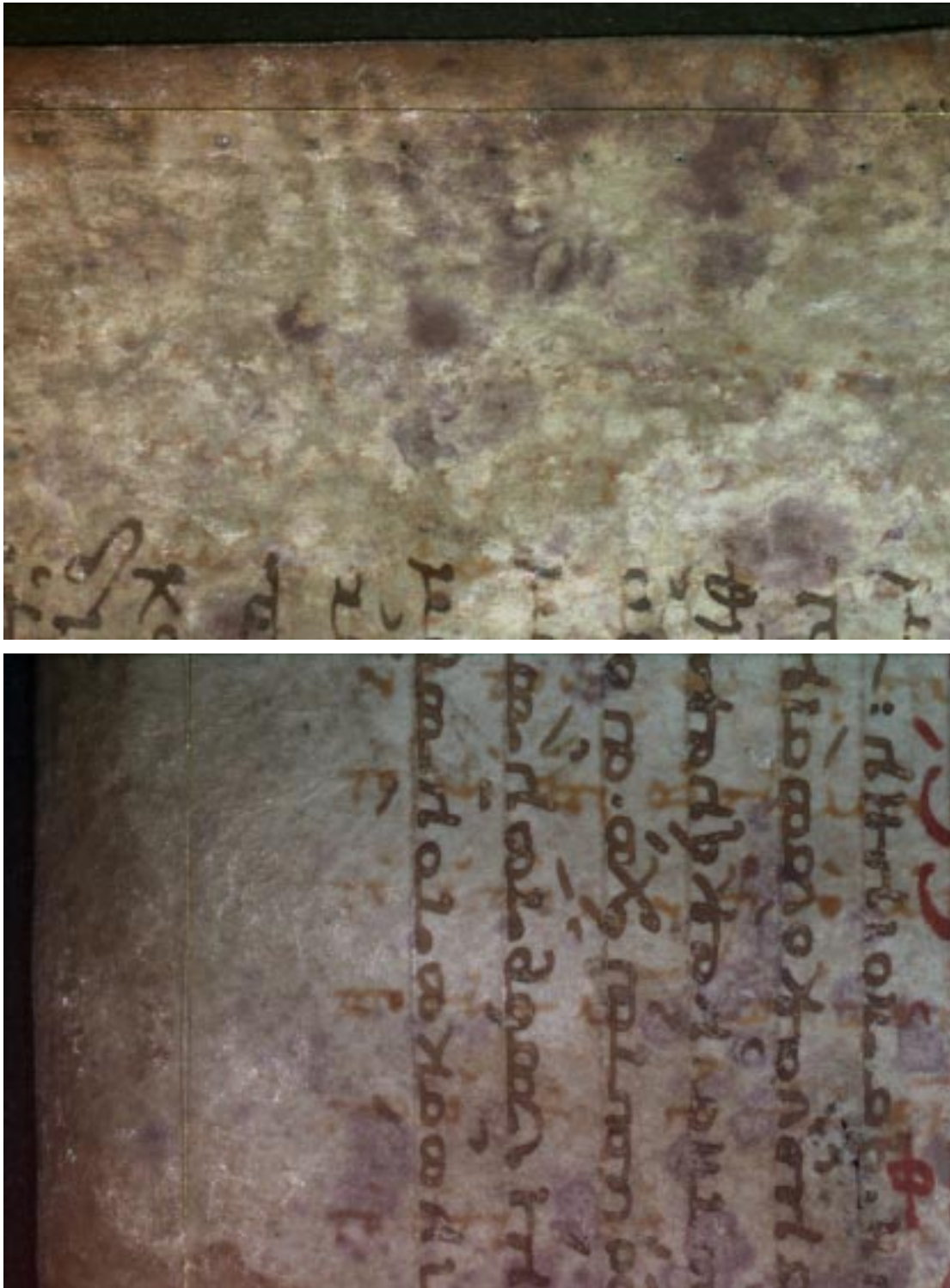


Figure 7. Synthetic RGB images, which were constructed by placing individual narrowband LED images into each of the RGB color channels. By using different linear combinations of LED images, the visual appearance (color and contrast) can be manipulated.

D. Pseudocolor images

The Archie 1.1 software can be used to construct pseudocolor images from LED monochrome

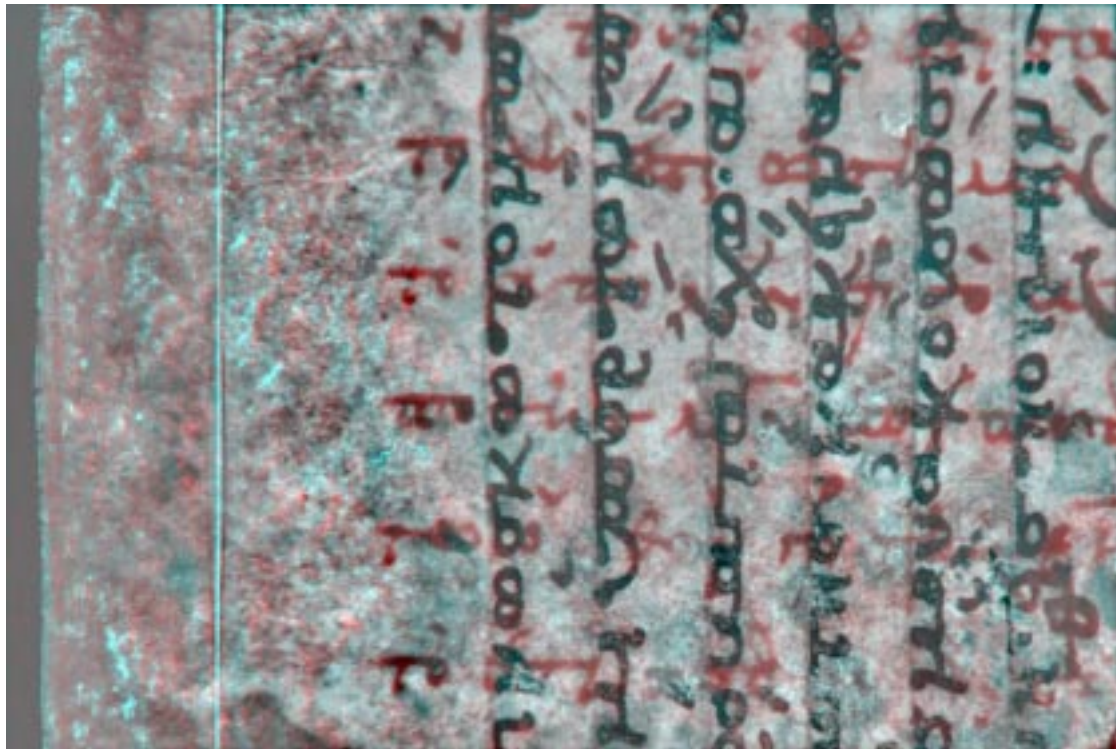


Figure 8a. Pseudocolor image constructed using LED and UV fluorescence monochrome images.

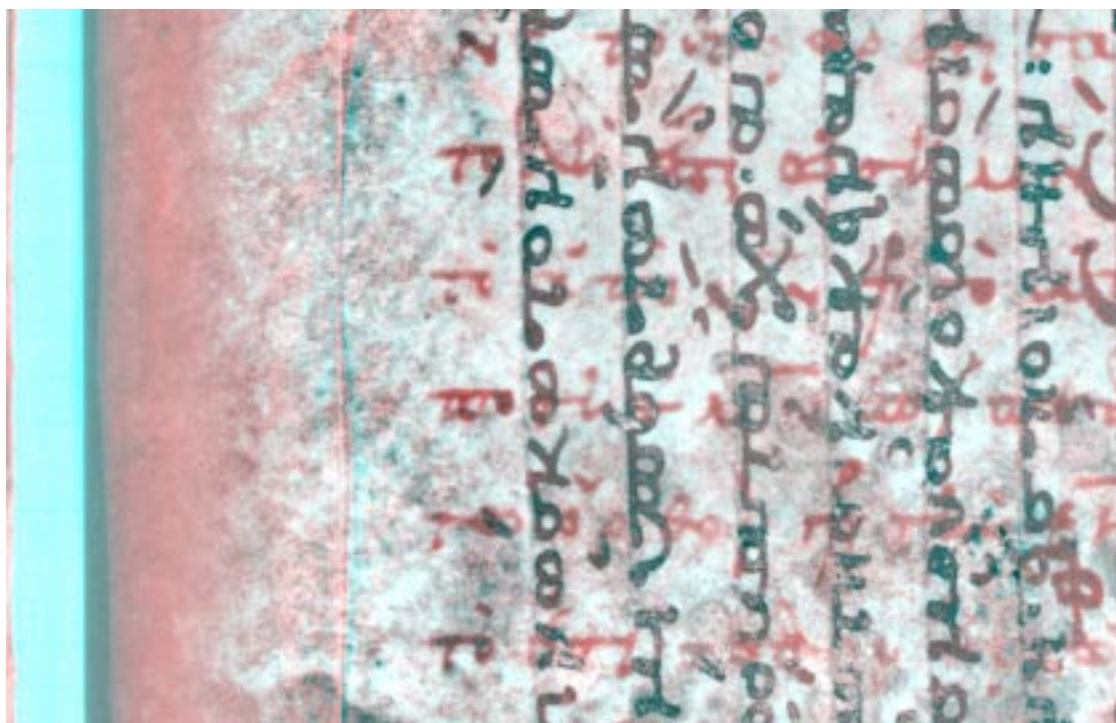


Figure 8b. Pseudocolor image of same region using production illumination with color camera.

images, in a manner similar to that used in production imaging to produce pseudocolor images from tungsten and UV images. Briefly, synthetic RGB images are constructed by placing selected monochrome LED, UV, and IR images into particular color channels of the RGB images; these RGB images are then input for processing by various Archie 1.1 commands (see the Archie 1.1 documentation for syntax and usage details). An example of a pseudocolor image produced in this manner is shown in Figure 8a. Contrast and visual clarity surpass that obtained using the broader bands available using our standard production imaging methodology (see Figure 8b).

E. Principal component analysis (PCA) from narrowband LED image sets

Principal component analysis was performed using PCA java plugin code (Michael Abràmoff, MD, PhD; <http://bij.isi.uu.nl/>) with ImageJ, a platform-independent software package widely used in the image science community (Wayne Rasband; <http://rsb.info.nih.gov/ij>).

A notable result of PCA analysis using the LED image sets can be seen between the left and right panels of Figures 9. In the left panel, the whole of the images was used to calculate the principal components before the subregion shown was selected. In the right panel, the subregion to be shown was isolated from the same image set before PCA calculations were performed. The calculations were performed identically, and no increase in contrast was used in producing these figures; the increase in contrast is due solely to the reduction in the size of the region being analyzed. Improved contrast in principal components was observed in other images processed in the same manner (data not shown) and is consistent with the basis of PCA analysis. Larger regions may have a broader range of content, with the set of classes adequate to decompose the content of one image region inadequate to describe the entirety of a larger image.

This observation is general, i.e. it is a fact of PCA and does not obtain from the use of LEDs in particular. This indicates that our practice, in performing PCA on whole images obtained using any type of illumination, may be improved by analyzing images subpart by subpart.

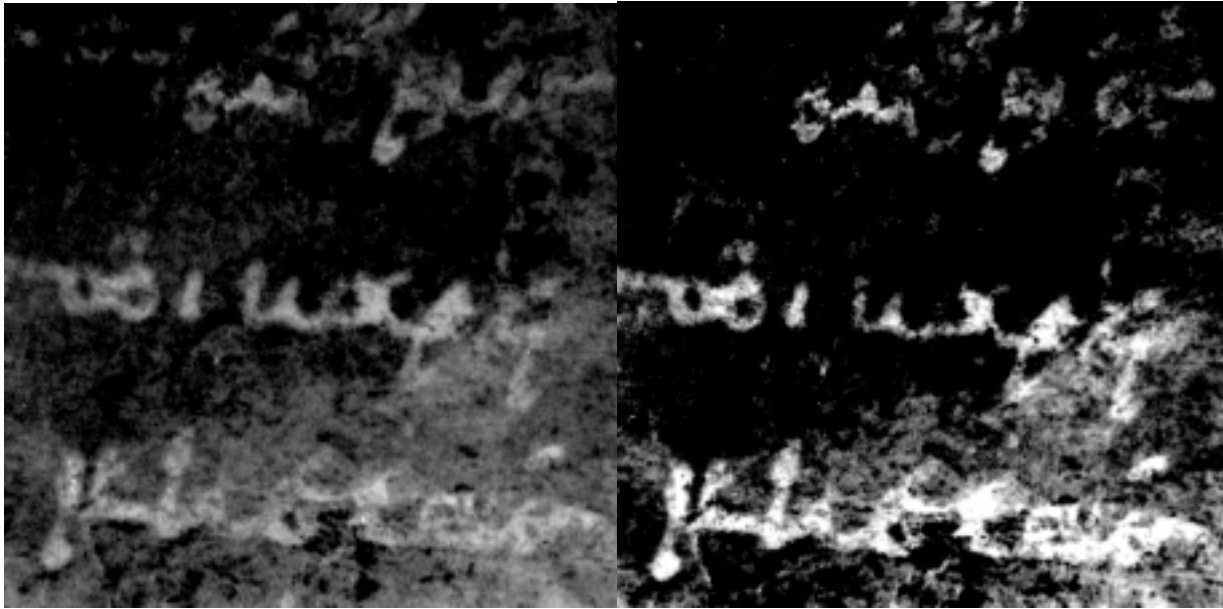


Figure 9. *Left panel:* section of a principal component image calculated using the entire areal extent of the input images. *Right panel:* principal component image calculated using just the region shown in the image. Note the increased signal content in the image calculated using a smaller input region.

CONCLUSIONS

Preliminary analysis points to several conclusions concerning the utility of LED illumination for the Archimedes Palimpsest project:

1. *LED illumination has led to incremental improvements but not breakthroughs in readability.* Results to date demonstrate advantages in comparison to results that have been obtained by other techniques (glass filter banks; liquid crystal tunable filter), which are evident in the few documentary results illustrated here. However, these analyses have not shown marked or material improvement upon prior efforts, in terms of allowing the scholars to read text that has not previously been readable.
2. *Acquisition of images is extremely rapid, and consistent with the logistics of the imaging effort.* Large numbers of images were acquired at a much higher rate than is done during the

production imaging based on tungsten incandescent light sources. This finding obtains even taking into account the small field-of-view of the Sensys camera (1536 x 1024 pixels versus 3020 x 2008 pixels for the Kodak DCS760) and the consequent need to acquire 4 times as many images to cover the same region. Use of the larger format Quantex camera (3072 x 2048 pixels), owned by RIT and advocated by Roger Easton, would eliminate this factor and reduce the required image count by a factor of 4. Acquisition speed also greatly exceeded (by a factor of more than 10X) that of filter-based multispectral imaging obtained during previous experiments. Operationally, the LED illumination method was a vast improvement over our previous work to produce data amenable to remote sensing analytical processing. This result alone argues for the use of LED illumination in future work.

3. *PCA suggests that processing of image subregions would improve results.* The mathematics of PCA indicate that analysis of smaller regions, which generally have less variation in content than large regions, can improve the results of variance-based identification of the content classes (color mixtures) comprising the image.

4. *Pseudocolor results suggest using LEDs with a monochrome camera.* Based on several results, it is recommended that future work (including "production" type imaging) employ LED illumination. Preliminary analysis showed no particular advantages obtain from the use of tungsten illumination in tandem with the DCS 760 color camera used in production imaging to date. The increased speed, better dynamic range, and avoidance of the Bayer mask built into the CCD sensor of the color camera all constitute improvements upon the current practice.

5. *Multispectral analytical techniques benefit from a larger number of wavebands.* The present work has been limited by the use of only 6 wavebands in the visible portion of the light spectrum. Given sufficient preparation time, an LED illumination system using larger numbers of wavebands could be constructed. The spectral resolution, and number of principal components, obtained in the present work suffered from the untimely demise of the "yellow" LED source (590 nm) that we had planned to use. As noted elsewhere, we relied on non-LED lights sources to obtain UV images, and also used a tungsten illuminator in combination to acquire images in the IR. LEDs in these wavebands are available, and future multispectral imaging projects would benefit by their inclusion.

6. *The availability of LEDs at further wavelengths is improving.* The availability of LEDs having spectral widths less than that of the filters (FWHM ~ 25 nm for LEDs versus FWHM ~ 50 nm for filters) improves the spectral resolution of remote sensing analytical techniques. A drawback is that we were not able to freely select the center wavelengths of LEDs; filters with arbitrary center wavelength are more easily obtained. During the last year, the range of wavebands that can be obtained using LEDs has increased, due to the introduction of new LEDs that reach into the ultraviolet and by the availability of LEDs that fill in holes in the visible spectrum.

SUMMARY

This preliminary analysis of images obtained using the LED illumination system has not yielded major changes in the readability of the undertext. Improvements to workflow, improvements to contrast in PCA, and the lack of downside suggest that LED illumination is to be preferred over the lighting schemes that have been used previously in the Archimedes Palimpsest work.