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Advances in Spectral Imaging Curve Analysis for Humanities Studies and Heritage Science

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Abstract

Establishing standardized digital protocols for Spectral Imaging creates opportunities for non-invasive analysis of a wide range of heritage and archival materials. In addition to the capacity to reveal hidden and non-visible information, the creation of spectral curves from the response of materials throughout the visible and non-visible wavelengths allows us to identify and characterize inks and colorants as well as track changes due to environment or conservation treatments. The use of spectral curves for this purpose requires a spectral library of reference materials that can be used for comparison and identification of these heritage materials. Advancing our capacity to non-invasively analyze documents, manuscripts, textiles and objects requires a rigorous standardized protocol that is reproducible and repeatable. Spectral curve analysis necessitates that all imaging metadata and parameters are consistent and materials are monitored to assure accurate replication.

Introduction

Developing and advancing non-invasive techniques is an ongoing challenge for heritage preservation. Spectral imaging is one of the techniques that was initially used for revealing hidden text and diagrams, but at the Library of Congress we have advanced this technique for characterization of inks and colorants, as well as the capacity to track change and degradation over time due to the impact of environment or treatments. In order to accurately characterize materials, a spectral library of materials for comparative purposes must be created. Since the spectral response of materials can change over time, the spectral library needs to include natural and accelerated aged samples, as well as pigment mixtures. Spectral un-mixing – the challenge presented when a colorant is a mixture of more than one pigment – requires pure end members for linear un-mixing, and non-linear requires specific modelling and an understanding of the interaction between pigments and their contribution to the curve analysis. This method requires a precise and repeatable procedure and addresses the challenges of integrating processes into existing workflows [1].

Defining Spectral Curve Analysis

A spectral curve is the visual representation of a medium's spectral data that illustrates the reflectance of light from its surface (y-axis) wavelength-by-wavelength (x-axis), forming a unique curve. The reflectance properties of any material will depend upon its physical and chemical properties. These unique curves make it possible to identify different materials – paper, inks, and pigments - by analyzing their spectral signatures and comparing to those of available reference samples in the form of spectral libraries. Additionally, two materials of a document or object that may visually look the same, can be compared to see if there are distinguishable differences between them. This type of analysis is also employed to track changes of materials over time; before and after an object is on exhibit, during natural and accelerated aging studies, or throughout conservation treatment periods.

Spectral Curve Software

Over the past 9 years the Preservation Research and Testing Division (PRTD) at the Library of Congress have examined, trialed, and compared a number of available imaging software packages and their ability to adapt to the needs of heritage science. One of the more powerful software packages is ENVI, a commercial software developed by Exelis for the analysis of geospatial imagery. This program has been adapted for application to the Library's cultural heritage documents because it is well integrated with the latest types of spectral imaging processes and provides good standardization of procedures. ENVI is the preferred software program we use for spectral curve analysis due to its advanced ability to build spectral libraries. Our spectral libraries are comprised of reference spectra of known papers, inks, and pigments, and when used in conjunction with ENVI's unique tool called Spectral Analyst, we are able to efficiently match an unknown spectrum to the materials contained in the spectral library.

The second software package we employ for spectral curve analysis is ImageJ, a java-based open source image processing software developed by the National Institute of Health. Its open architecture provides extensibility via Java plugins and recordable macros. While it does not come ready-made with advanced tools for spectral curve analysis, it does allow for a simple and manual procedure and notably greater access for a wide range of users due to the open source cost component.

These two software packages were chosen specifically because of their ability to facilitate operations that use multispectral image sets which are comprised of multiple registered images of the same region that have been captured using different wavelength illuminations. It is advantageous to manipulate such image sets in the form of image "stacks" (cubes) where many analytical and processing operations make use of multiple images of the stack simultaneously (with each image of a stack known as a "slice"). This enables a natural means to organize images and processing operations and this stack structure is critical for spectral curve analysis.

Spectral Curves for Characterization

Capturing the spectral response throughout the full wavelength range from spectral imaging allows the unique response of the material (pigment, ink or substrate) to be captured. A spectral imaging system was installed at the Library in 2008 and has been used extensively over the past nine years to image collection items, providing the range of spectral data needed for Library collections research [2]. The system utilizes a 50 megapixel monochrome camera integrated with light emitting diode (LED) illumination panels that cover the spectral range of 365nm to 1000nm – from the ultraviolet (UV), through the visible spectrum and into the near infrared (IR). The image capture software has been customized to address the needs of information and metadata required for the cultural heritage field. The full width at half maximum (FWHM) spectral curves for the individual LEDs ranges from ±3 to ±15nm. Remote sensing imaging spectroscopy has demonstrated that many surface features have diagnostic absorption features that are 20-40nm wide at FWHM, allowing spectral imaging systems that acquire data in bands of this width to provide sufficient resolution for direct identification of these materials [3][4]. All captured images are accurately registered, enabling almost unlimited combinations of spectral wavebands for processing and characterization

Characterization of pigments requires imaging of the cultural heritage object under the exact same illumination conditions as the reference materials in order to provide a direct comparison for identification. Figures 1-3 demonstrate the process used for characterizing unknown colorants on a 15th century hand-colored German woodcut. Figure 1 shows the woodcut and examples of reference pigments that are candidates for possible pigment matches. The spectra of these pigment samples, along with many others, comprise our historical pigments spectral library.

Figure 1. Unknown Color Palette of 15th Century German Woodcut Compared to Known Pigment Reference Samples

Figure 2 illustrates the capacity in ENVI to select a precise region of interest (ROI) to create the spectral curve of the unknown woodcut pigment. The zoom window is linked to the full page window to allow easy navigation of the image and ensures exact selection of pixels.

Figure 2. Selection of Precise Region of Interest for Spectral Analysis

Figure 3 shows the results of ENVI's Spectral Analyst tool as it calculates the closest matches of the unknown orange pigment to the contents of the spectral library and lists them in order of best match.

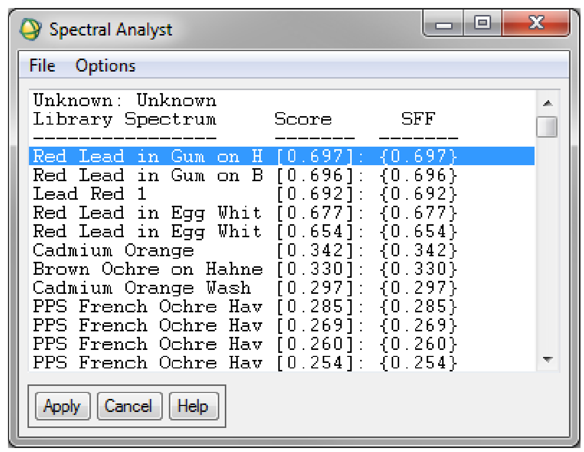


Figure 3. Spectral Analyst Function Showing Substantial Match of Unknown Spectra to Red Lead

Often, due to changes over time, impact of environment or treatment, or colorants on historic materials being mixtures of pigments, the spectral curve created is not a precise match between the historic material and reference material. In Figure 4, the unknown pigment spectra (black curve) from the woodcut is graphed against the results from the Spectral Analyst function (red, blue, and green curves). Though the results of Spectral Analyst overwhelmingly confirm the unknown pigment as Red Lead, the curves on the graphs are not the exact same shape. Curves can be difficult to interpret, as pigments on objects have aged and deteriorated.

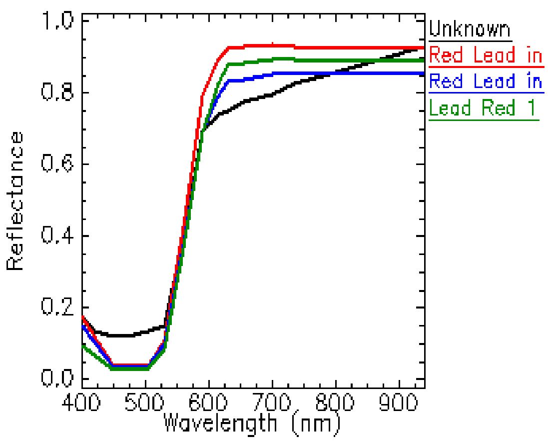


Figure 4. Spectral Curve of Unknown Pigment Compared to Matched Known Pigment Spectra

This change can be simulated by the accelerated aging of pigment samples. Figure 5 demonstrates how aging affects the shape of the spectral curve. Note specifically the significant shift in shape between 600nm-630nm.

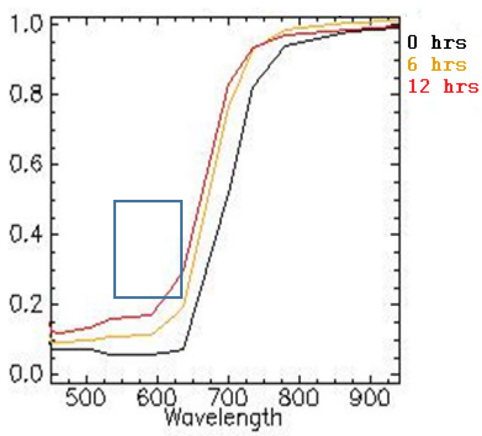


Figure 5. Spectral Curve of a Pigment at Multiple Stages of Accelerated Aging

However, accelerated aging doesn't always produce an exact match for the natural aging occurring in historic objects. It becomes critical to examine the points of inflexion when comparing curves to allow for accurate interpretation of the best match. The application of the pigment on the substrate causes additional impact on the shape of the spectral curve. Thick, opaque applications produce a more pure curve while the spectra of thin washes can contain interference from the substrate even when the spectra of the substrate is subtracted out. The document shown in Figure 6 incited the question of whether the thumbprint belonged to the author of the text. When spectral curve comparisons were made between the ink of the thumbprint (red curve) and the ink of the general main text (green curve), there was not a close match. However, when the ink of the thumbprint was compared specifically to regions of thinner ink of the main text (blue curve) there was a positive match.

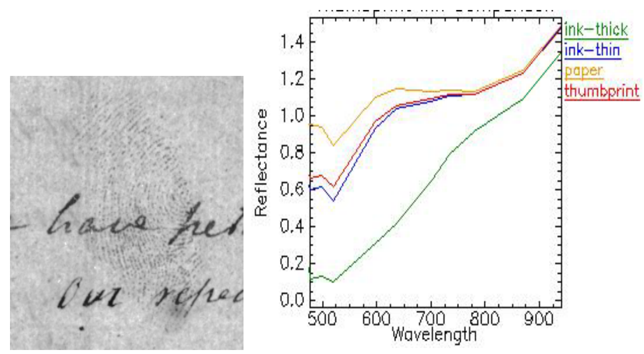


Figure 6. Thumbprint in Ink as Seen in 370nm and Spectral Curve Comparison of Document Ink and Paper Components

Spectral Curves for Tracking Change Due to Treatment or Environment

Comparing changes due to treatment or environment is a new development for non-invasive preservation analysis and assessment. Figure 7 shows an area of a document treated to remove areas of discoloration. The exact same pixel location was selected in the regions of interest before and after the treatment. A nearby region of untreated paper was also selected to assure no change occurred due to the treatment. In Figure 8, the spectral curves show no change in the area of untreated paper (red and black curves), indicating no other impact on the historical material. However, the curves of the region where the treatment occurred (green and blue curves) shift towards resembling the shape of the pure paper response indicating that the treatment was successful and did not impact the substrate. This capacity to assess minute changes during the process of a trial treatment greatly enhances our ability to assure the impact of treatments. Further aspects of this process include creating reference materials that have been treated and assessing them before and after accelerated aging to assure that the treatment will not change or have any detrimental impact on the historic materials at some time in the future.

Figure 7. Selection of Same Pixel Location Before and After Treatment

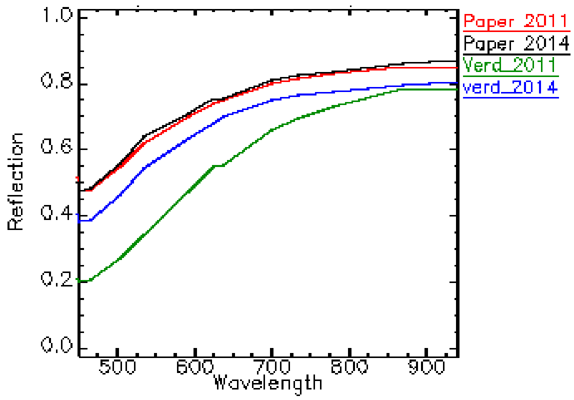


Figure 8. Spectral Curve Response Before and After Treatment

This process has also been applied to the assessment of materials on exhibition. Objects that contain light sensitive materials can be more susceptible to conditions experienced during display. Figure 9 depicts a section of an object that contains light sensitive pigments. The object was to be exhibited for six weeks and was imaged before and after display. Though no change was visible with the unaided eye, spectral curve analysis revealed minute change to one of the pigments. This analysis lead to prolific discussion of the implementation of additional preservation measures in exhibition display. When this object went back up on permanent exhibit, it was fitted in an anoxic encasement and motion detection sensors were attached to the display lighting, set to turn off when no one was viewing the object to reduce exposure to light.

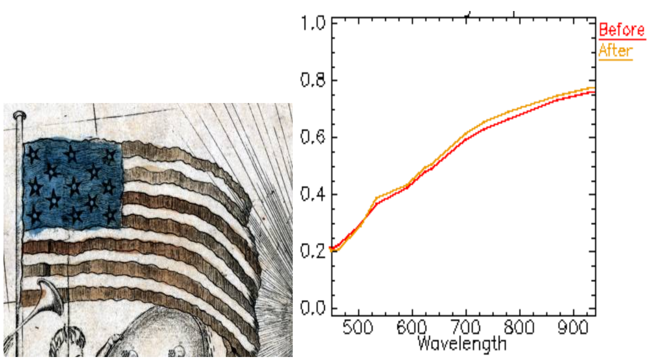


Figure 9. Spectral Curve Comparison of Light Sensitive Pigment Before and After Exhibition

Spectral Reference Library

The creation of a spectral reference library is part of the Library of Congress's development of the Center for Library Analytical Scientific Samples (CLASS). To ensure open access and sharing of data, the spectral library can also be saved in .txt format, uploaded to the CLASS-D database, then made available for downloaded by institutions who don't have the opportunity to make their own pigment reference samples. As illustrated in Figure 11, this data can then be imported into a spreadsheet for comparison to unknown spectra on an object obtained from the ImageJ procedure outlined below.

Creation of a Standardized Procedure

PRTD staff have been actively involved in sharing these processing techniques through training workshops and it was quickly realized that the capacity for spectral curve analysis needed to be available in open source software formats. The process for spectral curve comparison was developed and standardized in the ImageJ software package for researchers who did not have the ability to obtain more expensive software. Though this process is without access to sophisticated features like ENVI's Spectral Analyst, Figure 10 illustrates how the ImageJ procedure allows for pixel selection of a region of interest and plotting of the Z-Axis Profile to obtain reflectance values across all the spectral wavelengths.

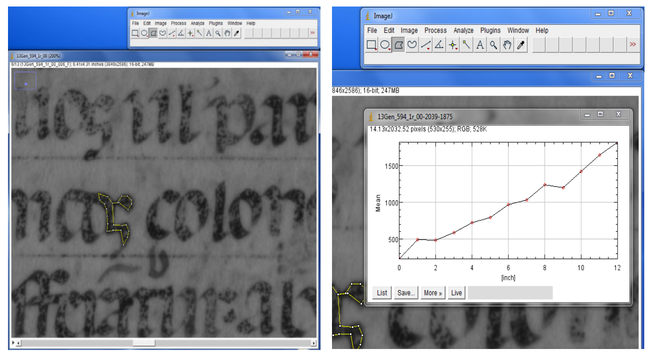
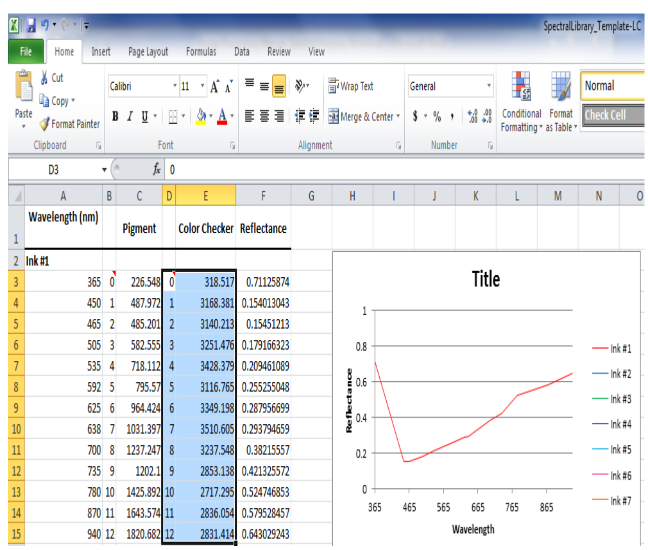


Figure 10. ImageJ Pixel Selection and Z-Axis Profile Plot

The z-axis profile data is then extracted and plotted in a spreadsheet with calculations performed to allow for standardization with the image's white reference material. Spectralon, a fluoropolymer with high diffuse reflectance across the UV-Vis-IR spectrum, is a white reference standard present in all multispectral images captured at the Library of Congress. This calibration process is required to allow materials to be compared accurately between different imaging sessions and assure accurate response across all wavelengths.



Wavelength (nm)		Pigment		Color Checker	Reflectance
Ink #1					
365	0	226.548	0	318.517	0.71125874
450	1	487.972	1	3168.381	0.154013043
465	2	485.201	2	3140.213	0.15451213
505	3	582.555	3	3251.476	0.179166323
535	4	718.112	4	3428.379	0.209461089
592	5	795.57	5	3116.765	0.255255048
625	6	964.424	6	3349.198	0.287956699
638	7	1031.397	7	3510.605	0.293794659
700	8	1237.247	8	3237.548	0.38215557
735	9	1202.1	9	2853.138	0.421325572
780	10	1425.892	10	2717.295	0.524746853
870	11	1643.574	11	2836.054	0.579528457
940	12	1820.682	12	2831.414	0.643029243

Figure 11. Calculation of Calibrated Spectral Curve via Spreadsheet

Conclusions

Advancing the capacity to use spectral imaging for characterization and preservation purposes greatly expands our ability to preserve library, archive and heritage materials. Spectral imaging for non-invasive analysis has become a quick and accurate assessment method to both characterize and identify colorants and inks, as well as examine changes due to treatment, environment, or exhibition. The creation of a spectral library of reference materials that can be used for comparison and identification of these heritage materials is a critical component for this process and is being further developed to expand the capabilities for identification of materials. The development of a rigorous standardized protocol that is reproducible and repeatable in different software packages allows greater access to this process and assures accuracy and consistency. Developing and advancing non-invasive techniques is critical for heritage preservation, and aided with the utilization of imaging technologies.

References

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Author Biography

Dr. France, Chief of the Preservation Research and Testing Division (PRTD) at the Library of Congress, researches spectral imaging techniques and addressing integration and access between scientific and scholarly data. An international specialist on environmental deterioration to cultural objects, her focus is connecting mechanical, chemical and optical properties from the impact of environment and treatments. Serving on standards and professional committees for cultural heritage she maintains collaborations with colleagues from academic, cultural, forensic and federal institutions.

Meghan Wilson, a Preservation Specialist in the Preservation Research and Testing Division, has specialized in spectral imaging and image processing for over 6 years. She has established guidelines and documentation of work processes for equipment and image quality control to ensure high quality standards for spectral imaging. Her work has advanced the development and implementation of data and metadata management tools and workflows for advanced digitization programs around the globe, supporting imaging systems at international institutions as an independent consultant.

Chris Bolser, a Preservation Technician in the Preservation Research and Testing Division at the Library of Congress, applies his forensics background to the analysis of cultural heritage materials. He is proficient in an array of image processing techniques and has contributed to the development of standards and procedures of preservation analyses.