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A Multispectral Scanning and Post-Processing Workflow for Historical Film Colors

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KEYWORDS: DIGITIZATION // MULTISPECTRAL SCANNING // FILM COLOR // COLOR SCIENCE // CULTURAL HERITAGE

Abstract

A multispectral digitization workflow that uses a uniform distribution of spectral bands across the visible spectrum can significantly improve results and provide reliable documentation of heterogeneous archival color film stocks. It also enhances versatility for innovative renderings compatible with future projection technologies. Reducing subjective interventions in film digitization remains a cornerstone of restoration ethics. Multispectral scanning directly leverages the information embedded in historical film stocks, enabling a robust, material-based technology that respects the unique properties of each film element. An integrated multispectral digitization and post-processing chain supports physically accurate rendering of scans by including measurements from various cinema projection illuminants. The goal of this workflow is to represent the color appearance as it would have been perceived on the cinema screen. Building on more than a decade of research into the technology and aesthetics of historical film colors and scanning, we have integrated this knowledge into a practical solution.

Over the last two decades, developments in film scanners have been largely incremental, even as the business model and areas of application have changed fundamentally.

Most professional film scanners in use today were conceived for chromogenic negative stocks intended for the Digital Intermediate Workflow of the early 2000s. When film production shifted fully to digital, scanner manufacturers repurposed their systems for archival use, making only minor modifications to their mechanical and optical designs. As digital technologies advanced and cinema projection also transitioned to digital, the dissemination of archival films became fully digital as well. This created a still ongoing prolific field: Millions of hours of archival film require digitization, supported by both national initiatives and private funding schemes.

Yet despite the demand, awareness of the specific requirements of historical color film stocks—by which we mean all the film color processes invented and in use before the mid-1990s—has remained limited.

The vast majority of the hundreds of color processes developed throughout film history differ fundamentally from chromogenic negatives. Their dyes and pigments exhibit idiosyncratic spectral characteristics that current scanners cannot comprehensively capture. Some of these colors are located outside of current standard color spaces (DCI-P3, BT.709, BT.2020). As a result, scans often fail to provide a complete and uncompromised representation suitable as a starting point for post-processing (Fig 1).

A new approach is therefore essential—one that spans the full spectral range of historical films and pays special attention to their illumination. In film projection, the material composition of a film and the optical light path of the projector, combined with a specific illuminant, together define a film's unique appearance on the cinema screen.

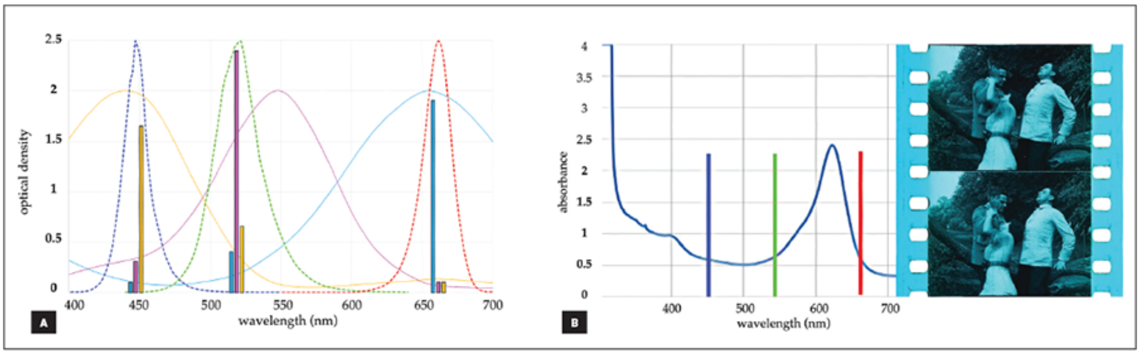


FIGURE 1. *(a) illustrates how a single pixel of a CMY-based film is captured by a film scanner with typical RGB spectral sensitivities. Each dye layer contributes to the recorded signal according to its optical density and the scanner's RGB sensitivity curves. Within each channel, the individual dye contributions are summed to produce the final response. Because these scanner sensitivities differ significantly from the human eye's color-matching functions, the captured colors cannot accurately reproduce those perceived by a human observer. (b) Certain early applied colors used in tinting and toning, hand-and stencil coloring can even fall between the spectral sensitivities of RGB scanners completely.*

Multispectral scanning addresses this challenge by recording the spectral characteristics of historical color films using a condensed illumination beam and providing the foundation for rendering the resulting scans with different projection illuminants used throughout film history. The ultimate aim of digitization is to recreate, as closely as possible, the appearance of the film as experienced in theatrical projection.

Equally important, every digitization must adhere to the core principles of restoration ethics: documentation, transparency, and reversibility.[1-3] Subjective interventions should be minimized. A rigorously science-backed workflow—combining multispectral scanning with coherent, well-documented post-processing stored in a human-readable form within the metadata file—is essential to meet these ethical requirements. It also provides the only path to producing future-proof digital elements capable of adapting to emerging standards in color management and new display technologies.

Configuration of Multispectral Scanning Hardware and Systems Control

Basic Requirements

What are the ideal properties of scanner hardware developed specifically for historical color film stocks?

In one of our previous studies, we investigated the most established traditional scanners interacting with various color film stocks.[4] As a result, we established a catalog of parameters for scanning devices optimized for archival films, with particular emphasis on accurate color representation.

Mechanical layout: The transport system should prevent physical damage by operating with low tension and precise optical control. A sprocketless, pinless film path is required to ensure gentle handling while enabling frame-by-frame capture with a series of spectral bands.

Illumination: The system must include an array of spectral bands spanning the entire visible range, with an additional infrared channel for detecting scratches and dust in silverless color film stocks. To replicate cinema projection, the optical path should provide collimated illumination and a uniform light path.

Spatial resolution and image geometry: Resolution should be high enough to capture local details, i.e., ≥ 2K for 16 mm film and ≥ 4K for 35 mm film. Full edge-to-edge scanning is mandatory to include precious color information and analog metadata present in the perforation area. Once the film is digitized without this information, it is nearly impossible to identify film stocks later or trace the genealogy of a film element.

File output: The camera should generate unprocessed, radiometrically linear monochrome image data at a bit depth > 12, ideally 16-bit, with each spectral band recorded separately, in an uncompressed, well-documented—i.e., publicly available detailed specification—and sustainable file format designed for long-term preservation without the risk of obsolescence.

Modularity: All components should follow a modular design to allow integration of new cameras, illumination systems, and optics, enabling adaptation to both the diversity of film stocks and emerging standards and technologies.

The user interface and controls need to guide experienced scanner operators through a rigorously defined process and restrict options to scientifically validated parameters, thus excluding subjective interventions.

Traditional film scanners only partly meet these requirements. Most of them are not well adapted to the brittle condition of archival films. But most critically, the accurate capture of historical film colors remains the most neglected aspect of their technology.

The Quest for Color Authenticity

Film is an inherently ephemeral medium

Film elements undergo continuous transformation during their lifespan—degradation, decay, fading, shrinking, and damage such as scratches, dirt, and microorganisms. Each element also carries its own genealogy, often poorly documented and requiring assessment and research by a trained film historian, archivist, or curator. Negatives, positives, and intermediate elements can co-exist in multiple versions. Distribution positives printed from original camera negatives or intermediates contain the intended color characteristics, provided they are unfaded and printed on the designated stock at the time of their production. Original camera color negatives, on the other hand, provide the highest spatial resolution and dynamic range but lack crucial information needed to reproduce a film's authentic aesthetics. This discrepancy arises because a) printing stocks differ among one another in their spectral sensitivity, their sensitometric characteristic, their dynamic range, and their dye spectra from negatives, and b) post-processing steps such as color grading and chemical development determine the color aesthetics of a positive print, which is different from any intermediate element.

The situation is even more complex when we consider the hundreds of mimetic historical color processes. Mimetic color processes, often referred to as natural colors, are characterized by a photochemical chain dedicated to match the visual perception of a scene as closely as possible. Some of them use black-and-white separations as source material, with color applied only during the production of exhibition prints in the lab, for instance, Technicolor's dye-transfer process. Earlier, applied colors were added to each individual black-and-white print manually through tinting, toning, hand or stencil coloring, producing prints with widely varying palettes.

The color-forming dyes and pigments embedded in the emulsion layers of positives do not always pair precisely with the complex color-physical properties of the associated negative original. They produce side absorptions that hinder ideal colorimetric reproduction. Inter-image effects between layers in the film stocks further contribute to their nonlinear response, albeit to a lesser degree.[5] Because of this non-linear and often arbitrary relationship—especially in non-chromogenic two- and three-color processes and in chromogenic film before the 1950s—each color film stock exhibits its own idiosyncrasies, which we describe as its material aesthetics. Even two exhibition prints produced using the same method can appear markedly different, as numerous factors in the post-processing chain influence the final result.

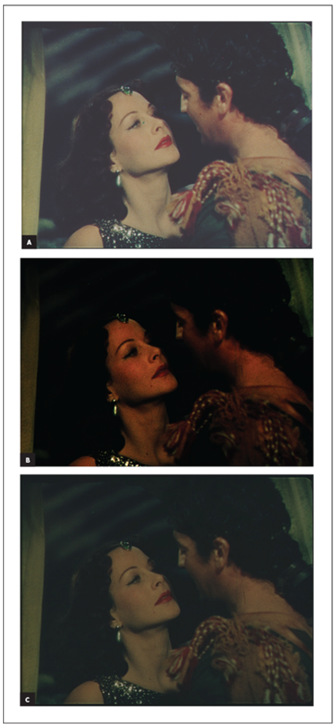


FIGURE 2 (a-c): Comparison of three major professional film scanners: The scanners produce different results without documentation of their optical properties and their proprietary image processing. The outcome is also highly dependent on the scanner operator's expertise and decisions. RGB scans of a Technicolor No. IV dye transfer print of the trailer of Samson And Delilah (1949).

An advanced, historically conscious scanning workflow must therefore prioritize the capture of the color information in exhibition prints. Yet most commercial scanners were designed for chromogenic negative film stocks with lower optical densities up to 2, and some cannot adequately record the higher densities of exhibition positives, which can exceed 4.[6]

While the first step in an advanced, restoration-ethical scanning workflow must be informed by the material and technical properties of the historical film stocks to be scanned, the second step must focus on illumination. It needs to consider the spectral power distributions of the illuminants in the scanner and the light sources in analog cinema projectors, as well as their optical paths.

Aiming at translating the analog colors of historical films into the digital domain, therefore, needs to take into account all these key factors pertaining to the source elements and their presentation on the theater screen.

Illumination is a Key Factor

What appears on the cinema screen is colored light, defined by the interaction of projector illumination and the spectral absorption of dyes and pigments in the film. Illumination is thus a decisive factor in digitization.

As mentioned earlier, most traditional film scanners employ only three or four narrow spectral bands, leaving sensitivity gaps. As a result, they fail to capture the variability of spectral responses in historical stocks. Because these bands are hardwired into the scanners' mechanical layout, they also limit the versatility of a science-backed capture device.

Furthermore, scanner illuminants are rarely documented, and proprietary image processing embedded in hardware and/or software introduces black-box operations that make it impossible to document the color management chain, thereby violating the principles of restoration ethics (Fig. 2).

An advanced multispectral scanner covers the entire visible spectrum, ideally with evenly spaced or adjustable spectral bands, as documented in the metadata file. It supports both collimated and diffuse illumination; the optical path of the illumination is crucial for certain film stocks. So-called collimated illumination produces directed rays of light and thus replicates the optical configuration in projection light, while diffuse light reduces the visibility of mechanical damage on the film element (e.g., scratches and dirt) and is therefore preferred in traditional scanners. As we reported in an earlier paper, the optical path not only influences local and global contrast for certain film stocks but also affects the film's hue due to the so-called chromatic Callier effect, which is wavelength-dependent.[7] The Callier effect influences the color rendition for film containing scattering elements, such as metal pigments in toned film or any silver-containing film stocks (Fig. 3).

At various stages of scanner development, we tested different illumination setups.

Our first experimental design (ERC Proof-of-Concept VeCoScan, Grant Agreement number 812583) applied a linear variable bandpass filter (Schott Veril S200) covering the spectral range from 400 to 700 nm. This filter selected spectral bands with an FWHM of approximately 18 nm from the emission of a Light Emitting Plasma bulb (HPLS345 High-Power Plasma Light Source and 5 mm Liquid Light Guide). By shifting the filter through a narrow slit in front of this broad-spectrum plasma source, we illuminated the film material with 25 spectral bands, producing a corresponding series of 25 monochrome high-resolution images. Each image represented one spectral band under either diffuse or collimated light. Combining these methods—using a directed illumination path alternately scattered close to the film through a translucent, spectrally neutral diffusion filter—yielded 50 monochrome images per frame. While this setup offered the best coverage of spectral properties with variable light adjustments, it proved impractical for real-world applications. The design's additional moving parts increased vulnerability to physical damage. They slowed the operation, and in addition the resulting data volume was excessive and partly redundant, especially given the films' frame rates of 16 to 24 fps.

FIGURE 3: *Comparison of a stencil-colored and toned film in diffuse (left) and collimated illumination (right) shows the chromatic Callier effect. Multispectral scan of a stencil-colored and toned print of Le Pied De Mouton (1907), Library of Congress, rendered with the spectral emission of a Kinoton FP30 xenon illuminant.*

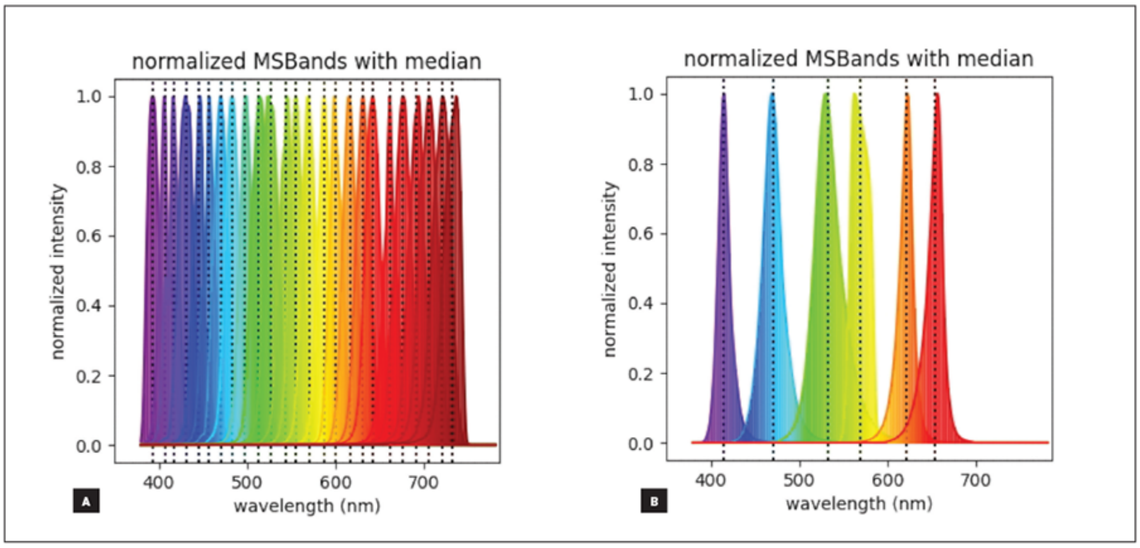


FIGURE 4. *(a) Spectral emission of the linear variable filter and (b) the six LEDs normalized values with median after calibration.*

To address these limitations, we introduced a selection of LEDs into the optical design, reducing the number of spectral bands and enabling rapid, pulsed illumination without moving parts. However, they also present physical constraints. For various solid-state reasons, the two common LED materials, i.e., InGaN LEDs (used for blue and green) and InGaAlP LEDs (used for red and orange), are highly inefficient at the yellow-green peak wavelength of 565 nm. LED manufacturers, therefore, rarely produce such LEDs, and even when available, their use is generally impractical because of their low efficiency. For this reason, green LEDs in video projectors and yellow LEDs in automotive turn signals are now produced almost exclusively using the same technology as white LEDs.

Not only are LED's emission properties limited, but they also tend to change their spectrum depending on the working temperature. Careful selection is therefore mandatory. Furthermore, commercially available LEDs that meet the specifications as outlined above leave a gap in the green-yellow region between 530 and 590 nm, which must be filled using interference filters. In practice, 6 to 10 evenly spaced, narrow spectral bands are sufficient to map the visible spectrum between 400 and 680 nm and produce accurate colors. The LEDs flash into a mixing rod for even distribution, after which the light is condensed and directed via a mirror system to produce collimated illumination. As in the previous design, a translucent white filter for diffused illumination is inserted alternately close to the film.

Each illumination unit's spectral bands are measured using a Qalif Spectro spectroradiometer, which captures a range from 380 nm to 780 nm with a color accuracy of ±0.0015 for CIE 1931 xy and a luminance accuracy of ±1 % (Fig. 5 a-b). The data points from these measurements are exported, converted into text files, and incorporated into the workflow software for metadata documentation and visual rendering. This approach guarantees transparency, sustainability, and reversibility in multispectral image processing.

Calibration

In the calibration process preceding each scanning session, the integration time for each spectral band is determined by a series of flashes of increasing intensity to normalize the spectral response. This procedure enables full use of the sensor's dynamic range, increasing the signal-to-noise ratio while preventing overexposure in bright image areas or pinholes, which should be avoided according to DIN SPEC 15587.[6] Integration time values are stored with the project data and documented in the metadata file (Fig. 4).

The flat-fielding process involves capturing white and black frames without film to calculate transmittance values and compensate for uneven illumination in the image-forming area.

Rendering

Whereas traditional digitization workflows require extensive and time-consuming color grading after scanning, multi-spectral scanning enables the calculation of color values corresponding to the spectral transmission of the scanned film through a dedicated rendering pipeline.

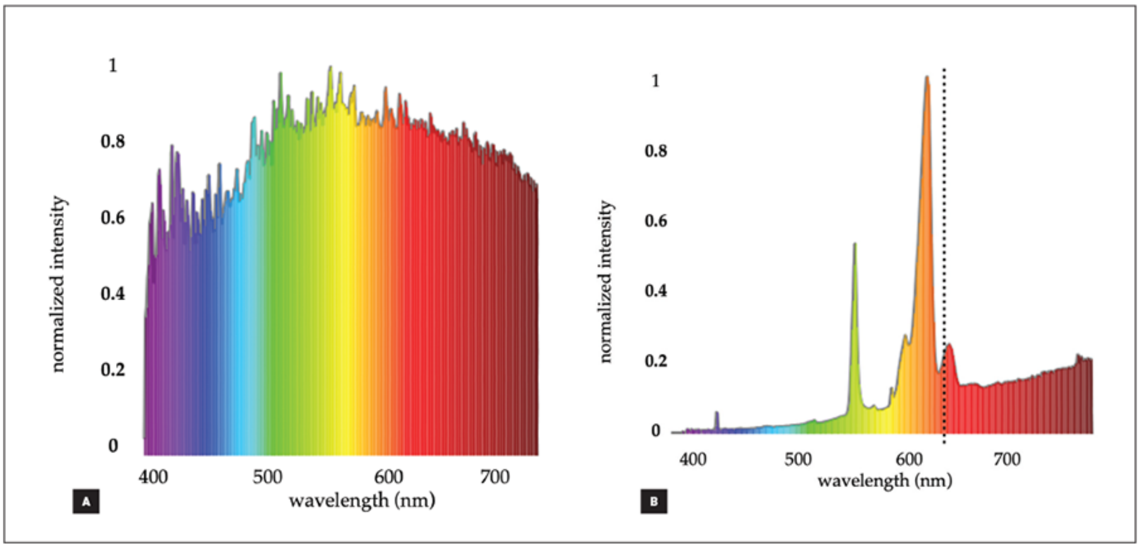


FIGURE 5 (a–b). Measurement of the spectral power distribution of a) a high-intensity carbon arc projection illuminant averaged over 11 measurements, b) a limelight projection illuminant with median (dotted line). Executed with a Qalif Spectro spectroradiometer.

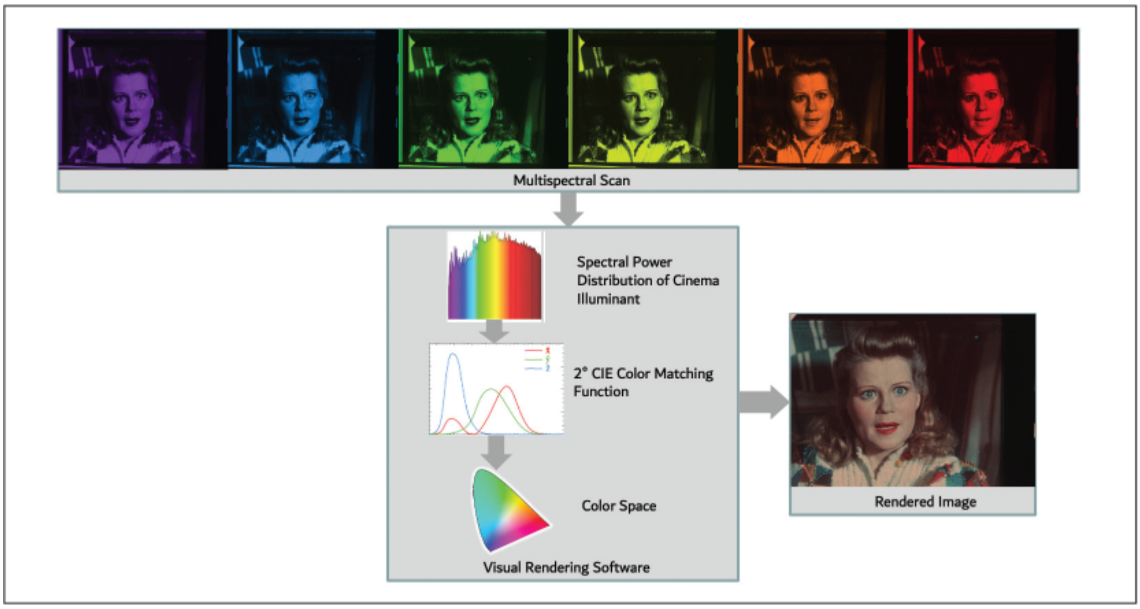


FIGURE 6. *Visualization of the multispectral rendering process: Six monochrome images representing the corresponding spectral bands (color-coded for better interpretation) are processed in the rendering software to produce an image using a specific projection illuminant and the color matching function.*

Color grading in conventional digitization workflows presents several problems. It is costly, requiring several experts and expensive color-grading suites, and, more critically, it introduces subjective judgments. Such subjectivity undermines a cornerstone of restoration ethics: transparency. Transparency requires the intersubjective communication of decisions and interventions applied during the digitization/restoration process. More often than not, grading decisions are based on visual inspection of the scanned film or a reference print on a viewing bench in front of an LED light panel. A scientifically rigorous workflow eliminates the need for color grading by directly computing color values from multispectral scans, as elaborated in this section.

The final rendering results still allow for curatorial adjustments after the scientific workflow is complete. Transparency requires that these additional steps be grounded in expert knowledge and fully documented. Enhancements such as increasing saturation, sharpening, and other alterations must be identified as remastering. Customers may request adjustments to suit contemporary viewing preferences or to adapt content for distribution platforms that differ from cinema projection, a common practice driven by economic demands. These additional processing steps can be accommodated, provided the unaltered multispectral raw scans and scientifically derived renderings are safeguarded in the processing package, accompanied by expert documentation of the metadata for each version.

Once the film has been scanned multispectrally—frame by frame, with a series of narrow-band illuminations in diffuse and/or collimated light as mentioned above—the resulting stacks of monochrome representations need to be processed to produce a color rendition that matches the source film as projected on the cinema screen (Fig. 6). Color values are computed from the transmittance images using colorimetric calculations that account for the illuminant and the color-matching functions for a 2° CIE 1931 standard observer. Renderings are output in established image file formats such as DPX or TIFF as tristimuli (DCI-XYZ) or RGB values (DCI-P3, BT.709, and BT.2020) and can be ingested into any major video post-processing and color grading software.

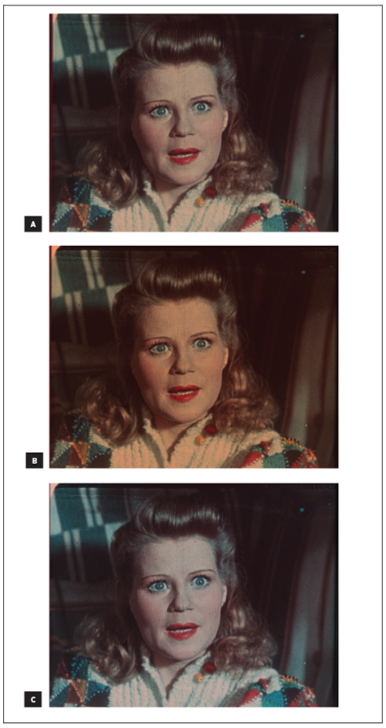
The visual rendering software incorporates measurements of the spectral power distribution of typical illuminants used in cinema projectors throughout film history. These measurements were carried out with a Qalif Spectro spectroradiometer that recorded the light reflection from a Spectralon tile using a collection of historical projection lights. The set includes carbon arc (high-intensity arc and low-intensity arc),[8,9] limelights, halogen light, incandescent light, xenon, pulsed super-high-pressure mercury lamp, metal halide sources, and later extended to include additional lights—halogen illumination, LED light panel. For instance, we measured carbon arc illuminations at Kinemathek/Lichtspiel in Bern, Switzerland, using a historical Westrex Master 35mm projector (Century Projector Co., Ashcraft Manufacturing Co., NY) from their collection, recording both low- and high-intensity arcs.[10]

Any light source can be measured and transferred into the rendering software via a Python-based transcoding script. This enables the rendering pipeline to be adapted to any curatorial requirement. In non-standard exhibition contexts—particularly for experimental films—curators may wish to recreate a specific analog viewing experience. Renderings can be calculated using any of these illuminants, chosen based on historical knowledge of a film's premiere screening, curatorial decisions, or intended distribution format—cinema, home theater, TV set, computer screen, or mobile device.

The rendering software includes a color-matching function for standard observers the CIE1931 2° CMFs.[11] These parameters must be recorded and communicated in the metadata file in a human-readable form.

When transmittance spectra are sampled at intervals of 5 nm or less, the CIE recommends computing tristimulus values with the standard summations once an illuminant and an observer have been specified. For lower-resolution spectra—such as those obtained from a 10-band film scan—various deconvolution and interpolation methods have been proposed to refine the spectral interval and improve the accuracy of the resulting colorimetric values. However, these approaches often require a color target to achieve a meaningful improvement.

For each frame scanned with seven bands, fourteen uncompressed 16-bit images (seven per light geometry) with a resolution exceeding 4K generate a data volume of more than 420 MB. In the context of film scanning, where tens of thousands of such datasets may be produced, streamlining the computational pipeline becomes essential. To this end, we tested a more efficient color calculation method that, instead of upsampling the transmittance spectra, downsamples the illuminant and observer functions to align with the spectral bands. Once an illuminant and a standard observer are selected, the CIE recommends applying standard summations to compute the tristimulus values. This approach covers the range from 380 to 780 nanometers, with a step size of 1 nanometer. A detailed description of the color calculation is reported in a previous publication.[12]



FIGURES 7 (a–c). Comparison of multispectral scans (diffuse illumination) rendered with three different illuminants—(a) high-intensity carbon arc (b) low-intensity carbon arc, and c) xenon light (below)—of an Agfacolor Duplichrome print of the film OPFERGANG (1944). Credit: Gert Koshofer Collection.

Depending on the intended viewing environment—such as an office, a living room, or a theater—the user can choose the most appropriate tonal response curve. For instance, a gamma of 2.6 is typically recommended for cinema projection, while a gamma of 2.2 has been used for the images presented in this paper.

FIGURE 8. *Split-screen projection of a multispectral rendering (left side) and an analog projection (right side) of a Kodachrome Two-color nitrate film at the George Eastman Museum's Dryden Theatre. For the comparison, the xenon projection light was measured with a Qalif Spectro spectroradiometer and ingested into the multispectral rendering software. FLUTE OF KRISHNA (1926, Anonymous). Credit: Item 1975.0007.0127 from the George Eastman Museum.*

The color images in Figs. 7 (a-c) and values are calculated with different illuminants.

We tested the results by projecting multispectral scans side by side with analog film to verify the accuracy of the rendering pipeline (Fig. 8). In an early study, we convened three focus groups representing distinct areas of expertise: film historians, curators, and archivists; film technicians and colorists; and color scientists and physicists. Starting with the 25 bands mentioned above, we found that six bands provided satisfactory results while remaining manageable in terms of data volume and processing time.

Style Transfer

Film digitization and restoration often face the challenge of combining different source elements—negatives, interpositives, internegatives, or projection prints—that vary in sharpness, dynamic range, and color rendering. Each type of element contributes distinct strengths: camera negatives usually provide the highest image quality and completeness, while exhibition prints more accurately reflect the color adjustments made for narrative functions, consistency, and aesthetic preferences.

Multi-sourced Aesthetic Transfer (MAT) addresses this challenge by transferring the color palette of a reference element (often an exhibition print) onto a higher-quality source scan (such as the camera negative). This process integrates structural fidelity with historically authentic color, ensuring technical quality and respecting the historical source material.[13]

The workflow involves:

- Selecting representative frame pairs from source and reference materials.
- Capturing them with high-quality, color-accurate scanning methods.
- Registering and aligning frames for pixel-to-pixel correspondence.
- Generating look-up tables (LUTs) to minimize color differences—1D LUTs for straightforward cases, 3D LUTs for more complex color transformations.
- Applying these LUTs in color grading software across the full film sequence.

In combination with multispectral film scanning, MAT offers a robust methodology to harmonize disparate film elements. The outcome is a digital rendering that balances aesthetic coherence, historical authenticity, and high technical quality—preserving films as they were intended to be experienced.

Conclusion

A scientifically rigorous multispectral digitization and post-processing workflow offers a sustainable path for translating historical color films into the digital domain. This approach not only captures a detailed amount of spectral color information embedded in a film stock, but it also establishes a foundation for present and future renderings that aim to reconstruct a film's authentic color appearance on the cinema screen. By incorporating measurements of historical projection illuminants directly into the visual rendering software, the workflow enables consideration of diverse exhibition contexts. Accurately encoding the full spectrum of film colors—including those outside the gamut of current display technologies—ensures compatibility with future technological innovations, such as multi-primary displays, wider color gamuts, and other emerging standards. Finally, by producing a series of transmittance images for each spectral band, the workflow remains device-independent and safeguards optimal sustainability for long-term storage, preservation, and continued access.

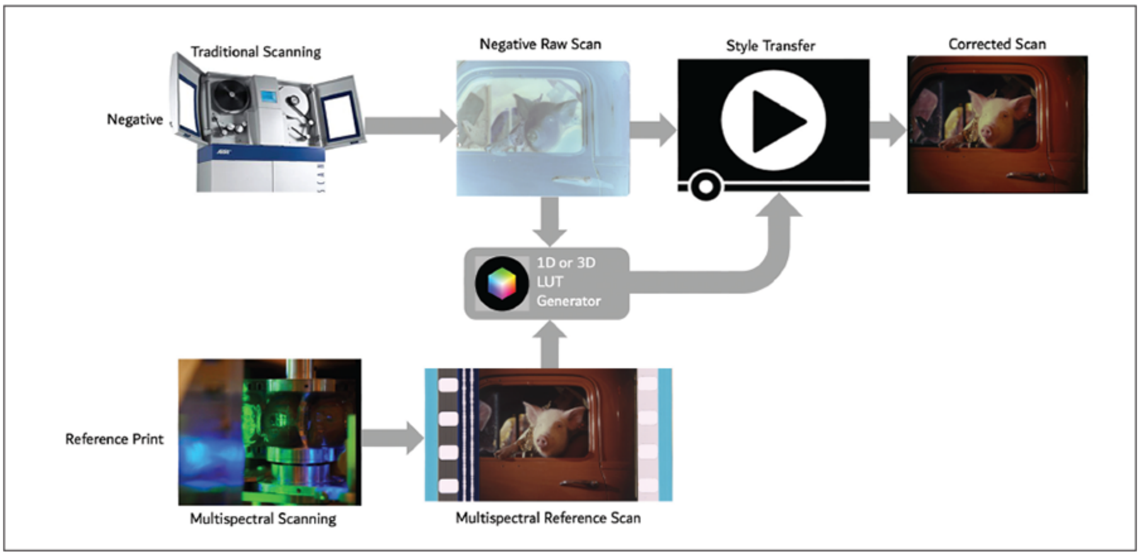


FIGURE 9. *Test case of BIG TOP PEE-WEE (1988), top left negative scan, bottom left represents the multispectral scanning of the reference print; top right is the result of the combined 1D LUTs; the bottom right is the output after applying the 3D LUT. (Courtesy of Paramount Pictures Corporation.)*

Challenges in real-world applications include processing speed and the volume of data produced. However, practical workflows demonstrate that these challenges can be mitigated through parallel processing and outsourcing of data storage. Another unexpected obstacle was the abrupt obsolescence of certain off-the-shelf components, such as cameras or lenses.

Our experience with archival institutions – including the Academy Museum of Motion Pictures, the British Film Institute National Archive, the George Eastman Museum, and San Francisco Film Preserve – shows that this advanced multispectral imaging technique addresses a growing interest in scientifically grounded and historically accurate digitizations of color films. Competitors have expressed interest in integrating the multispectral technology into their workflows and products.

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