Received: 7 February 2024 | Revised: 3 June 2024 | Accepted: 23 June 2024
DOI: 10.1002/col.22946

RESEARCH ARTICLE

Color systems for motion picture film digitization: A critical review

Alice Plutino

Department of Media Studies, University of Amsterdam, Amsterdam, The Netherlands

Correspondence
Alice Plutino, Department of Media Studies, University of Amsterdam, Amsterdam, The Netherlands.
Email: a.plutino@uva.nl

Funding information
European Union's Horizon research and innovation program (European Research Executive Agency), Grant/Award Number: 101105533

Abstract
Digitizing motion picture films is a crucial aspect of archival practices. Nevertheless, the primary purpose of this process is to convert analog film into a digital signal suitable for recording back onto film. Thus, the most popular color film system encoding, such as Cineon or Academy Density Exchange (ADX), may present some limits for the preservation and restoration practices. In this paper, Cineon and ADX systems are summarized and analyzed, and an experimental application conducted on modern cinematographic film scanners has been made to evaluate the integration of these encoding systems into these devices. Results have been examined and discussed to underline the constraints and possibilities of these color encoding systems for archival purposes.

KEYWORDS
cinema, film restoration, film scanning, motion picture film scanners

1 | INTRODUCTION

Considering the Kodak Milestone timeline, the first reference to the Cineon color system is dated to 1993. Here, it is reported that "*Using Kodak's new CINEON Technology, Kodak technicians digitally restored Walt Disney's 1937 classic Snow White and the Seven Dwarfs*."[1] This system has been used to create the so-called Digital Intermediate (DI) to modify and edit cinematographic materials, like in the popular *O Brother Where Art Thou?* (Ethan Coen and Joel Coen, 2000). From a financial point of view, the development of this system was a commercial response to Sony's marketing of the NTSC digital standard, which aimed at imposing digital formats over analog film productions since the presentation of Sony's first digital camera in the 1990s.[2] The Cineon system comprised a high-quality scanner for converting 35 mm film into digital format, a computer workstation equipped with software for image manipulation, and a laser recorder for retransmitting the processed images onto film.

In 1995, Glenn Kennel defined Cineon's conversion format,[3] later standardized by SMPTE in the DPX format.[4]

As reported on the Cineon patent,[5] it is "*[A]method of transferring an image recorded on a photo film to a digital signal*." Cineon's main goal is to produce a duplicate negative that matches the quality of the original camera negative (i.e., full latitude). To accomplish this goal, the negative film was acquired using a telecine scanning process (with CCD sensors or linear line sensors), which transformed the film transmittances into a voltage, amplified, and modulated to be displayed on a cathode ray tube monitor or recorded onto magnetic tape for storage. In the Cineon system, the telecine device has an output data pathway that processes the signal using a 1D LUT that transforms the video's tonal range to "*a more film-like tone scale such that the* *resulting negative produced will print out onto a photographic print element and look at least somewhat like a film system image.*"[5]

The 1D LUT applied in the Cineon system uses printing densities, thus a density representation that simulates the red, green, and blue channel responses in the printing process. Cineon Printing Densities (CPD) are defined by the spectral sensitivities of the 5384 film print, the spectral radiance of a printer (Bell & Howell Model C with a Wratten 2B UV filter), and the 5248 negative film base density.

In 2014, the diffusion of digital cinema led to the development and standardization of Academy Color Encoding System (ACES).[6] It is a color management and image interchange system applied today to movie production workflows. Among all the possible applications of ACES, it has a framework dedicated to film scanning and film printing processes. It was primarily used in film processing laboratories and is now relevant in the film preservation field.[7] ACES integration with the photochemical film process is very similar to the Cineon system. Still, the CPD has been replaced with a new densitometry for photochemical negative and internegative films, the Academy Printing Density (APD). APD are used in the Academy Density Exchange (ADX) system.[8–10] Similarly to CPD, APD are used to reproduce the "*optical density of the motion picture film material as seen by the material onto which the film material is printed.*"[11] APD are based on (1) the spectral power distribution of a Bell & Howell C printer lamp house with dichroic filters (like in CPD); (2) the spectral transmission of an Eastman Kodak Wratten Filter No. 2B (like in CPD); and (3) the spectral sensitivities of contemporary motion picture print films such as those of the Kodak Vision family, the Fujifilm Eterna family, and the Fujifilm F-CP (differently from CPD).

Many modern film scanners are based on Cineon and/or ADX systems and present LUTs and conversions that use CPD or APD curves. In this paper, an analysis of the use of printing density curves is presented, together with a critical review of the use of these systems for archival purposes.

2 | CINEON PRINTING DENSITIES

Considering that Optical density is defined as:

$$OD = \mathrm{Log}_{10}(1/\mathrm{Transmittance}). \quad (1)$$

Cineon system is defined in 10 bit log format; thus, it is encoded in a range [01023] (1024 values) with a step which represents 0.002 of OD (defining a max OD of 2, the step is $1024/2.048 = 0.002$). An offset of 2.048 is employed to select the range of densities that are the *most meaningful* for motion picture negatives since this range corresponds to an exposure range of ≈ 3.72 log exp (≈ 12.4 stops) for a film of gamma 0.55.[5]

Considering,[5,12] the Cineon system can be summarized as in Figure 1.

The Cineon system has three main components: the scanner, the recorder, and the workstation. As mentioned, the **scanner** (i.e., the telecine) spectral response is designed to be very close to the printing density response. When a film is scanned, data are converted from linear space (i.e., exposure) to log space (i.e., density) using a 1D LUT (logarithmic). The scanner is always calibrated on a sample of the negative film base. In the **recorder**, the essential color characteristics are the output film's laser wavelengths and spectral sensitivity (e.g., Eastman color intermediate film 5244 and ECI 5243 film). The printing densities (CPD) are matrixed and used in a 1D LUT to convert log space data (densities) into exposure values to drive the laser modulators. The recorder is calibrated using a gray-scale pattern on ECI film compared to standard status-M densities. Since the laser exposure densities of the recorder are known, as well as the status-M densities (standard and measured), it is possible to create and calibrate the conversion matrices (i.e., LUTs). Cineon's **workstation** consisted of a high-

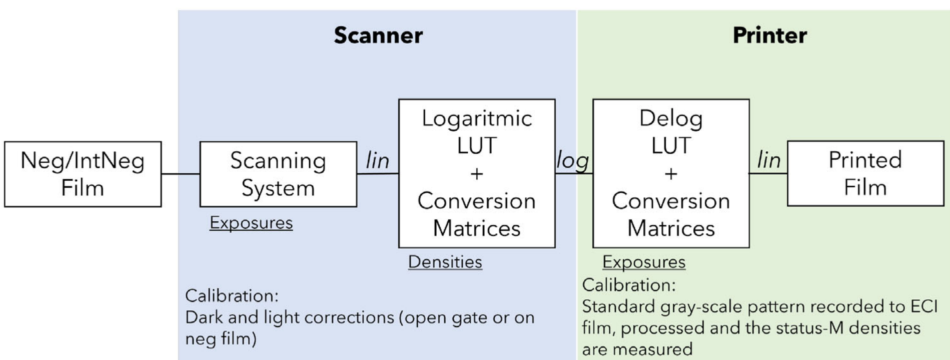


FIGURE 1 Graphical representation of Cineon system workflow.

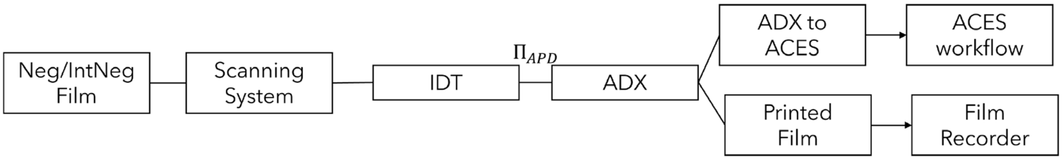
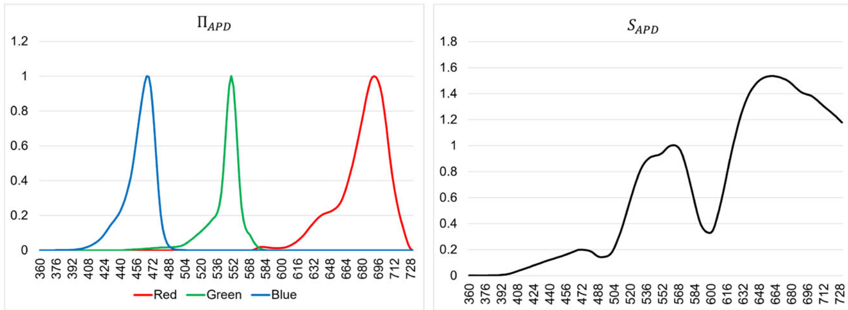


FIGURE 2 Graphical representation of ADX system workflow.

FIGURE 3 In (A) are plotted the spectral responsivities used to calculate APD (Π_{APD}). In (B) is plotted the relative spectral power distribution of the influx spectrum (S_{APD}) normalized to 1.0 at 560 nm.
Figures reproduced from the data provided in Reference 11.



(A) Spectral responsivities used to cal-culate APD.

(B) Relative spectral power distribution of the influx spectrum S_{APD}.

resolution display monitor calibrated to emulate the characteristics of a projected print (5400° K).

Quality control was performed using a specific set of negative densities, which are supposed to yield specific print densities (CPD): the Laboratory Aim Densities (LAD). LAD densities correspond to an 18% gray (i.e., the mid-density used in quality control) defined on [444, 444, 444] as the RGB 10 bit digital values representing LAD density on the negative. This process allowed for determining the correspondence between Cineon encoding and density, thus controlling and assessing the reproduction of tones in the Cineon system. When the Status M densities differ from the original analog film, generally because of the film stock, the negative has to be printed using different lights (see recorder calibration).

The core concept of Cineon revolves around the idea of precisely calibrating the scanner to represent the film printing densities of the target film materials accurately. The scope of Cineon was that the film print resulting from this process corresponds as much as possible to a print optically generated from a negative film element via the optical printing process.

Cineon Printing Densities are based on film stocks that are no longer manufactured, and the corresponding spectral sensitivities were never fully specified.[12]

3 | ACADEMY DENSITY EXCHANGE (ADX)

The SMPTE has developed the Academy Density Exchange (ADX), a densitometric encoding derived from Cineon.[8] ADX system is used to make an RGB encoding of motion picture color negative film within the Academy's Image Interchange Framework (IIF), thus, into the Academy Color Encoding Specification (ACES) values.

ADX system uses APD, whose spectral responsivities (Π_{APD}) are based on modern color negative and internegative film stocks.[11] The ADX system is generally considered better than Cineon since APD are compatible with contemporary film stocks and/or film stocks capable of being printed onto contemporary print films.

ADX system workflow can be summarized as in Figure 2.

To obtain ADX encoded images, scanners must have spectral responsitivities derived from Π_{APD}, or an Input Device Transformation (IDT) that converts scanner density values into APD densities. Π_{APD} depends on the film printing density metric, the spectral power distribution of a printer light source, the spectral transmission, reflection and absorbance of the printer's optics, and the spectral sensitivities of the print film stock. The reference Π_{APD} are reported in Figure 3.

Π_{APD} are spectral products (not discrete spectral components), which can be obtained as:

$$\Pi_{\text{APD}} = S \cdot s, \tag{2}$$

where, S is the relative spectral power distribution of the influx, and s is the relative spectral sensitivity of the receiver (all the components). In general, Π_{APD_r}, Π_{APD_g}, and Π_{APD_b} are used to identify the spectral responsivities of RGB channels of APD. APD values of color negative and internegative films can be obtained as[9]:

$$\mathrm{APD}_r = -\log_{10}\left(\int_{360}^{730} T(\lambda)\bar{r}(\lambda)d\lambda\right)$$
$$\mathrm{APD}_g = -\log_{10}\left(\int_{360}^{730} T(\lambda)\bar{g}(\lambda)d\lambda\right) \quad (3)$$
$$\mathrm{APD}_b = -\log_{10}\left(\int_{360}^{730} T(\lambda)\bar{b}(\lambda)d\lambda\right),$$

where, $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$ are Π_{APD_r}, Π_{APD_g}, and Π_{APD_b} normalized such that:

$$\int_{360}^{730} \Pi_{\mathrm{APD}_r}(\lambda)d\lambda = \int_{360}^{730} \Pi_{\mathrm{APD}_g}(\lambda)d\lambda = \int_{360}^{730} \Pi_{\mathrm{APD}_b}(\lambda)d\lambda = 1. \quad (4)$$

Subsequently, ADX encoding can be computed. ADX can be 16 bit—ADX16 [0, 65 535] or 10 bit—ADX10 [0, 1023] (SMPTE guidelines suggest using the 16 bit encoding whenever possible). ADX16 code values shall be transformed from APD values using[9]:

$$\mathrm{ADX16}_r = 1.00 \cdot \left(\mathrm{APD}_r - \mathrm{APD}_r^{Dmin}\right) \cdot 8000 + 1520$$
$$\mathrm{ADX16}_g = 0.92 \cdot \left(\mathrm{APD}_g - \mathrm{APD}_g^{Dmin}\right) \cdot 8000 + 1520 \quad (5)$$
$$\mathrm{ADX16}_b = 0.95 \cdot \left(\mathrm{APD}_b - \mathrm{APD}_b^{Dmin}\right) \cdot 8000 + 1520.$$

In general, an encoding offset of 1520 code values allows for a density range of 0.190000 below the measured D_{min} to be encoded, and the results are presented as INT. Furthermore, contemporary negative films do not have a standard behavior, so encoding gain factors are set as [1.00 0.92 0.95].[9]

It is possible to convert between other density metric values (e.g., status-M or scanner density) and APD. However, it is important to note that these transformations are product-specific and that separate transformations must be defined for each color negative or internegative film stock. Generally, the producer knows the scanner spectral responsivities in film scanners, and polynomial conversions are made to produce conversion LUTs.

4 | MODERN FILM SCANNERS

When scanning an internegative or negative film, some modern scanners combine the ADX system to make possible the integration of the scanner workflow in the ACES system or to reproduce the corresponding film print. Furthermore, the Cineon and the ADX systems allow the correlation between exposure values and densities (under specific constraints).

A general representation of modern scanners workflow is reported in Figure 4. Modern sensors, similar to the ones used in the Cineon system, capture a linear signal up to a threshold defined by the sensor sensitivity. The acquired signal is processed by internal (often proprietary) LUTs, which aim to encode it in the ADX color space (IDT-to-APD), transform the signal into log, or enhance colors and tones (e.g., apply a specific gamma value). Depending on the film scanner, the processing step can be unavoidable, controllable, or semi-controllable. In the first case, the processing is always performed, and the output image is often a log image with a specific gamma and, in some instances, color-corrected. On the other hand, when the processing is controllable or semi-controllable, the user can apply user-defined LUTs, and it is possible to obtain both the signal "*as the system acquires it*" or with user-defined corrections. After the processing, a Main LUT can be applied, and the user can define which editing applies to the image: if simulating the printing density (using Cineon-based or ADX-based LUTs); if obtaining a linear output; if applying a log curve of gamma 1/2.2 for television purposes; or others. The editing can be done manually at this step, intervening on the scanner's software curves (e.g., modifying the RGB lights, gain, gamma, or max and min densities).

Following the models provided by Cineon and the ADX system, in modern scanners, the definition of the values of D_{max} and D_{min} is fundamental. When applying *Print Dens* parameters, the output is usually a 10 bit image (derived from Cineon) with D_{max} 685 and D_{min} 95, while when applying custom parameters, the user can manually set the D_{max} and D_{min}. Even without considering the user-defined or custom-made processes, D_{max} and D_{min} will strongly affect the output image contrast and dynamic range. In addition, custom-made processings and default parameters are usually set to use the sensor's full potential without incurring noise or acquisition errors.[13]

4.1 | Experimental application

In this work, an ARRI AQUA test leader printed using an ARRILASER on KODAK Color Digital Intermediate film 2254 (negative) in 2017 has been used to test the presence of color systems in film scanners. The 21 ARRI AQUA gray-level frames have been measured in transmittance (360–740 nm) using a CM-36dGV spectrophotometer by Konica Minolta, and the ADX values for each of the 21 gray-level frames have been computed following Equations (3) and (5). Together with this measurement, the ARRI AQUA test leader has been acquired using nine

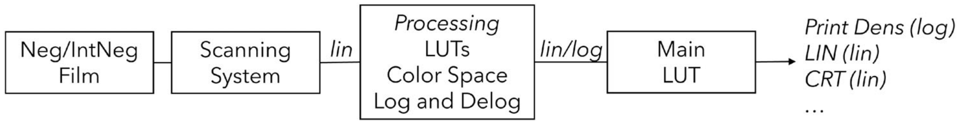


FIGURE 4 Graphical representation of a modern film scanner workflow.

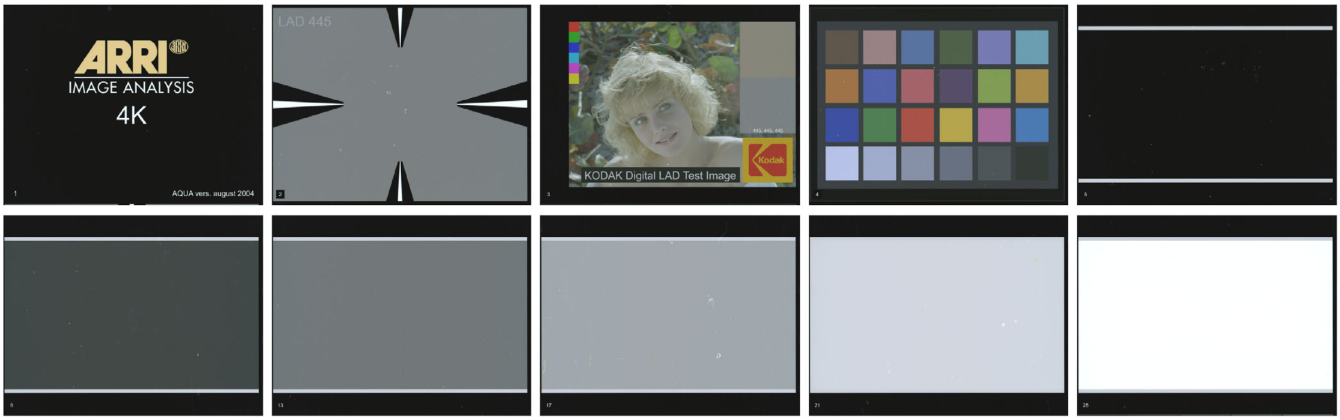


FIGURE 5 Representative frames of the ARRI AQUA test leader. The reported frames are Frame 1, 2, 3, 4, 5, 9, 13, 17, 21, and 25 digitized using scanner 1.

scanners (of six different commercial manufacturers) from different European laboratories. The 21 gray-level frames have been acquired using the scanner's default parameters or the laboratories' default workflow. The acquisition results in a positive image (see Figure 5).

In this paper, the commercial names and product details of the scanners will not be provided since this work aims not to compare different scanner manufacturers but to underline the similarities in the data processing operated by different machines. In general, the scanners of the same manufacturer (scanners 2 and 3; scanners 4 and 5; and scanners 6 and 7) have been grouped in the same plots. The acquired values have been scaled in the range $[0...2^{16}]$, and the results are presented in Figures 6–8.

Considering Scanners 1, 2, 3, and 4 (Figure 6), the trend of the acquired data compared to the computed ADX values is very similar, especially at high densities (dark grays). Here, the values are almost superimposable.

Considering scanner 5, of the same manufacturer as scanner 4 but probably used with different parameters, we can see that just rescaling the ADX values on the maximum value obtained through this digitization, we have the same ADX trend, at least for the POS acquisition. Some differences in tone reproduction can be noticed when using the IntNeg settings, which lead to higher values in the red and green channels, with a shoulder way before the saturation point. This behavior can be related to many phenomena, for example, the scanner's internal processing or a manual setting defined by the operator. In this case, further investigation is required.

In the case of scanners 8 and 9 (Figure 8), the acquired data follow the ADX encoding, and the data are superimposable to the measured ADX RGB. The only discrepancy in scanner 9 is probably related to a *flattering* of the acquired data operated by the user in order not to incur saturation error (like in scanner 5). This operation is related to the possibility of manually setting the D_{max} and D_{min}, which is largely used in modern film scanners (see Section 4).

Scanners 6 and 7 present the most different values of digits compared to the printing densities. In this case, the scanners do not apply the ADX encoding. From the shape of the curves and being aware of the film sensitometry, the data have been acquired linearly, and a standard conversion from negative to positive has been applied.

5 | DISCUSSION

From the experimental application reported in Section 4.1, it is clear that seven scanners of nine (five manufacturers of six) apply an ADX encoding when acquiring a negative film. The color encoding used in negative films by modern scanners is a very appropriate way to produce a film-like tonal range when digitizing modern films, and the results can produce high levels of fidelity when the APD curves perfectly match the film

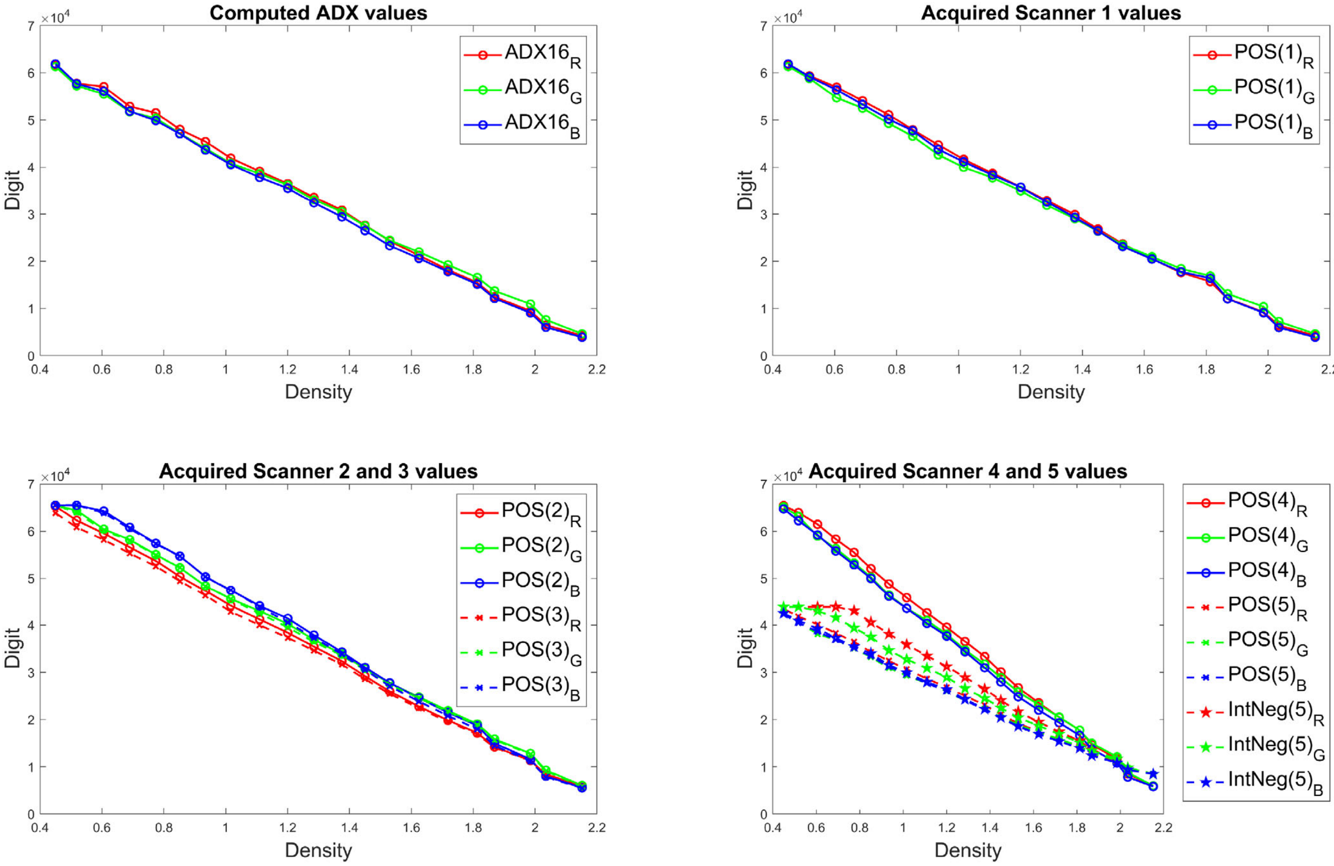


FIGURE 6 Representation of the RGB values of the 21 gray-level frames of the ARRI AQUA film, plotted in comparison to the density data. On the top left, the ADX RGB data computed from the transmittance measurements (Equations 3 and 5); on the top right, the RGB data acquired by scanner 1; on the bottom left the RGB data acquired by scanner 2 and 3; and on the bottom right the RGB data acquired by scanner 4 and 5. In this latter case, the acquisition with scanner 5 has been made using the "positive" (POS) setting and the "internegative" (IntNeg) setting. A more specific representation of scanner 5 data is reported in Figure 7.

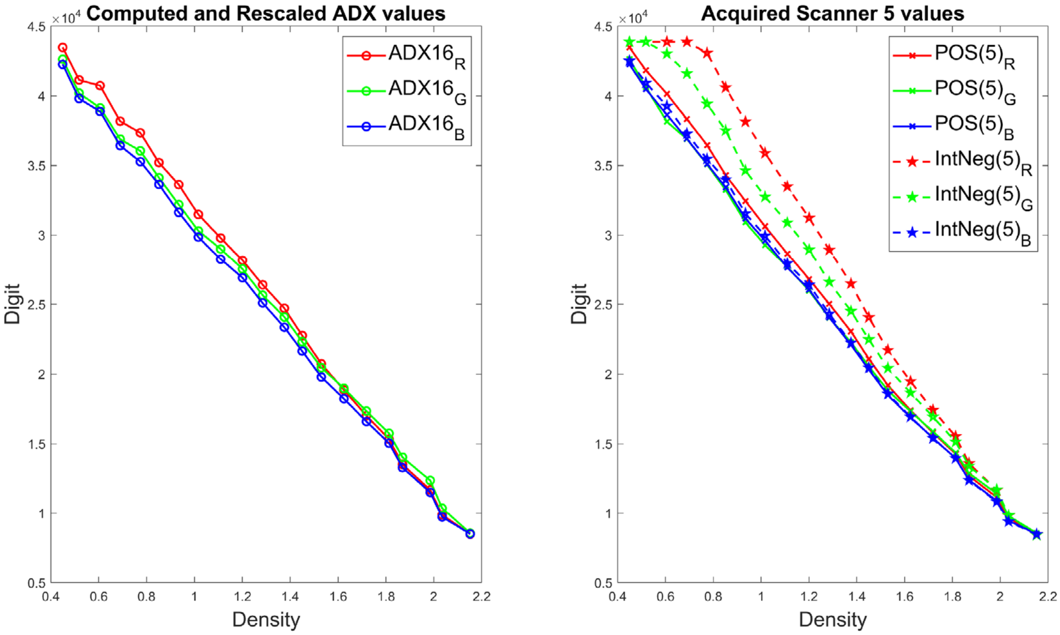


FIGURE 7 Representation of the RGB values of the 21 gray-level frames of the ARRI AQUA film, plotted in comparison to the density data. On the left, the ADX RGB data computed from the transmittance acquisitions (Equations 3 and 5). On the right, the RGB data acquired by scanner 5 are "positive" (POS) and "internegative" (IntNeg).

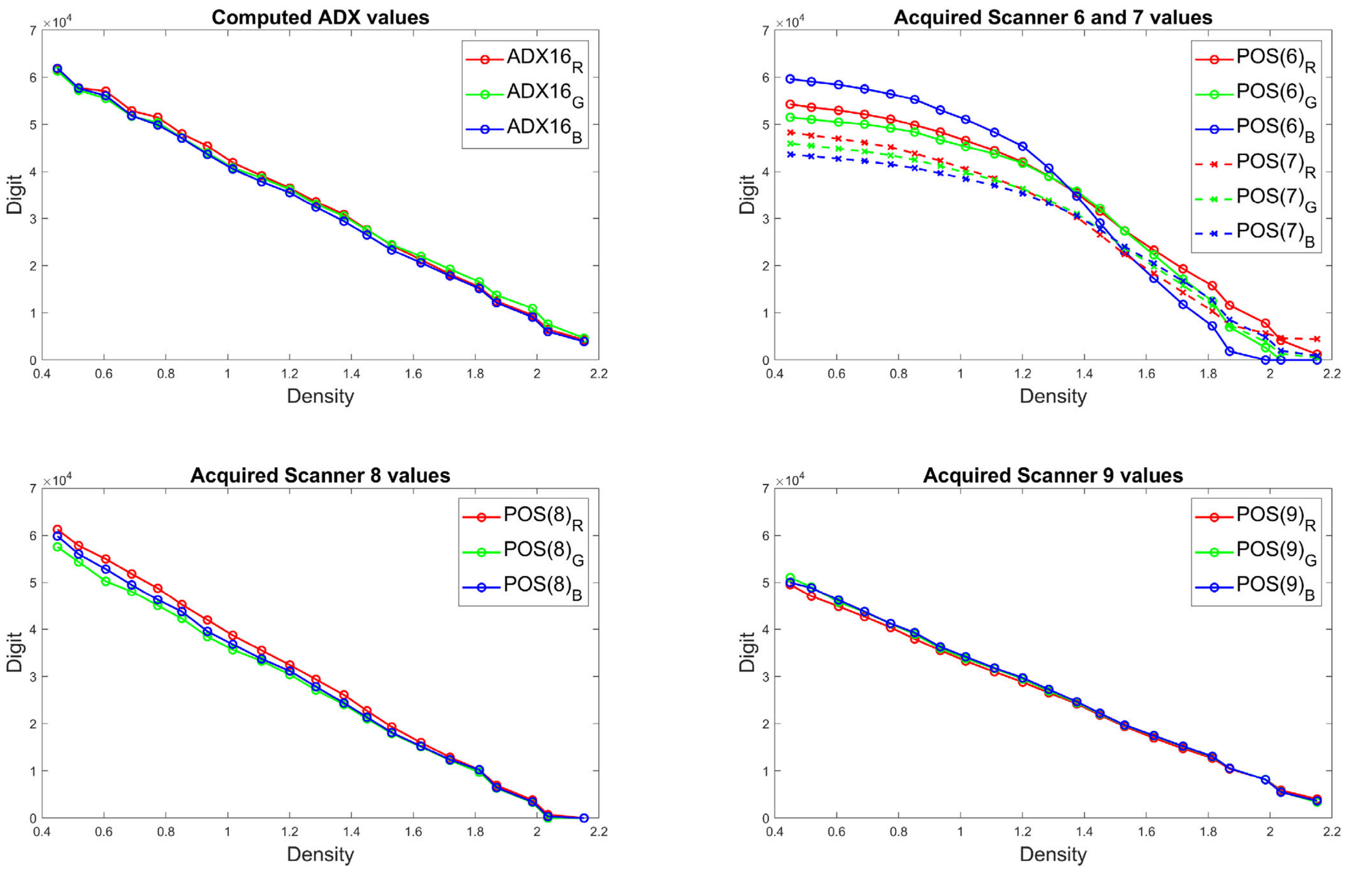


FIGURE 8 Representation of the RGB values of the 21 gray-level frames of the ARRI AQUA film, plotted in comparison to the density data. On the top left, the ADX RGB data computed from the transmittance measurements (Equations 3 and 5). On the top right, the RGB data acquired by scanners 6 and 7. On the bottom left, the RGB data acquired by scanner 8, and on the bottom right, the RGB data acquired by scanner 9.

densities of the positive. The ADX encoding in scanners' software can be referred to several ways, from *printing density curves* to *film sensitometric digital conversion* (see scanners User Manuals), and it can be easily applied by scanner operators and restorers providing satisfying results. In fact, this approach, when correctly applied, can easily lead to digitizations of good quality (given that all the digitization parameters are set correctly).

ADX encoding can easily simplify the digitization workflow, and many scanner companies provide not only APD curves but also film-related curves (i.e., based on specific film stock sensitivity curves) that simulate the most diffused film materials with high precision. From this point of view, working with suitable software that presents the possibility to set (or automatically identify) the film materials is as important as having high-quality digitization hardware.

The main issues in using the ADX system are related to the nature of the film materials.[14] As mentioned in the previous sections, APD are based on the spectral sensitivities of contemporary motion picture film prints, so when working with films from the early cinema or non-modern films, the tone reproduction may present artifacts and errors.[15,16] This happens because the ADX system has been developed for film production, not archiving. The digitization problem of non-modern films can also be related to the light sources implemented in film scanners, which have been selected to have an emission matching perfectly the APD curves, thus not being suitable for the digitization of all the historical cinematographic materials.[17–19] In this context, it is crucial to define digitization purposes and be aware of the scanned materials since applying the ADX system might not be the best solution. The suggestion is always to test the scanning system before proceeding with the acquisition and eventually proceed with a 16 bit[i] linear digitization using the system standard parameters and eventually proceeding with the negative–positive conversion or the colors and tones adjustment in the post-processing step.[20] This solution can also be suitable for positive film materials, which are not made to be encoded through the ADX system. In fact, positive films (e.g., release prints) carry not only the information related to the optical printing process (i.e., dye densities, printer features, and development process), but their color can also be the result of a process of color correction. For these reasons, it is recommended to preserve the colors and the tone distribution of the positive copies as much as possible during the scanning process.[21]

6 | CONCLUSIONS

This work presents a review of the main digital color systems used in motion picture film digitization. The examination of ADX and Cineon systems, together with an experimental application, allowed us to demonstrate the implementation of the ADX encoding in the majority of the analyzed scanners.

The experimental findings reveal that most scanners utilize ADX encoding for digitizing negative films, resulting in a film-like tonal range and high fidelity when matched with positive film densities. This encoding, available in the scanner's software, streamlines digitization workflows, with some companies offering specific film-related curves for precise simulation. Proper application of ADX encoding, alongside accurate digitization parameters, yields high-quality results, emphasizing the importance of both software capabilities and hardware quality in the digitization process.

The challenges with using the ADX system arise from its dependence on contemporary film materials, leading to tone reproduction issues when digitizing early cinema film and color processes, as well as non-modern chromogenic films. Additionally, the mismatch between light sources in scanners and historical film materials further complicates the digitization process. It is imperative for practitioners to carefully consider the purpose of digitization and the nature of the materials involved. Testing scanning systems beforehand and exploring alternative digitization approaches, such as 16-bit linear digitization followed by post-processing adjustments, can offer more suitable solutions, particularly for non-modern and positive film materials. By addressing these challenges and adopting appropriate strategies, restorers and scanner operators can enhance the quality and fidelity of digitized film materials, preserving their historical significance for future generations.

AUTHOR CONTRIBUTIONS

The author confirms responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon research and innovation program (European Research Executive Agency) under the MSCA Postdoctoral Fellowships 2022 (HORIZON-MSCA-2022-PF-01) agreement No. 101105533.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Alice Plutino https://orcid.org/0000-0002-6749-0783

ENDNOTE

[i] Following the main guidelines and digitization standards, the 16 bit quantization is suggested mainly for negative materials, while for positive ones the digitization can be made at 10/12 bit, depending on the laboratory policies.

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AUTHOR BIOGRAPHY

Alice Plutino (she/her) is an MSCA Postdoctoral Fellow at the Faculty of Media Studies of the University of Amsterdam and PhD in Computer Science (Università degli Studi di Milano, 2021). Her research interests are Color Science, Colorimetry, Image Enhancement, Image Digitization, and Archiving, with a particular interest in Cultural Heritage applications. She is the author of the book "Tecniche di Restauro Cinematografico" and of several journal and conference papers of national and international relevance. She is an Adjunct Professor at Università degli Studi di Milano and Centro Sperimentale di Cinematografia, teaching digital film restoration and digital media conservation. She is vice-president of the Italian Color Group (Gruppo del Colore), deputy editor of the Color Culture and Science Journal (CCSJ), vice-coordinator of Division 1, and coordinator of Division 8 of NC CIE Italy.

How to cite this article: Plutino A. Color systems for motion picture film digitization: A critical review. *Color Res Appl*. 2024;1-9. doi:10.1002/col.22946