Establishing Spatial Resolution Requirements for Digitizing Transmissive Content: A Use Case Approach

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Abstract

Guidelines for the digital conversion of transmissive content (negatives and positive slides) in the cultural heritage community have lagged behind those for print content. The primary reasons for this are twofold. Unlike print material, transmissive content is generally an intermediate format (as with negatives) or requires a viewing mechanism (such as a projector). In either case, there is no standard for the viewing of the object. The second challenge for digitization of transmissive content is, in large part, a result of the ambiguity of the visual output for slides or negatives. Typical guidelines for the resolution in digitizing transmissive content have concentrated either on the limits inherent in scanning equipment or attempted to base resolution on the microstructure (e.g., grain) of the negatives or slides, and not on the actual image information content in the film.

With special regard to the latter and in response to a project to digitize negatives from the Farm Security Administration (FSA) collection at the Library of Congress, the first part of this study investigated methods for establishing scanning resolution requirements for B&W silver-gelatin film negatives from the early to mid 20th Century based on defined use cases. The use case described by the curators of the FSA collection for resolution was based on the information content of the original photographic image and not on a film's granular microstructure. In other words, actual image information captured and not the inherent grain structure itself. This study describes the methodology used for determining the limiting resolution of film capture, and presents the results of the study for the FSA collection, as well as the application to all similar transmissive content. Examples will be provided to demonstrate the utility of this approach.

In addition to silver-gelatin B&W film negatives, the second category of transmissive photographic originals studied was early color positive processes, specifically Autochrome and Dufaycolor. The nature and perception of the image for these processes is very different than the typical image and silver grain structures of typical B&W negatives. In addition to the color information, these photographs represent a very distinct class of original and different use case requirements. Investigation of these materials provided an opportunity to expand the research methodology used for determining appropriate scanning resolution.

Introduction

One person's flower can be another one's weed. It all depends on the intended use. This same logic applies to determining required levels of spatial detail when digitizing image content from any form of photographic original, be it reflective or transmissive. To turn a phrase, one person's signal can be another one's noise.

Examples of this for reflective media are simple and few. An obvious one is choosing to digitize for paper structure (i.e. tooth) or simply the content provided by the original marking process. The latter is less demanding and almost in all cases more manageable and economical. Halftone structure is yet another. Are these flowers or weeds? Both can be considered of informational value, depending on who is asked, or an annoyance. The division lies in what can be considered of image value versus artifactual value.

Examples of transmissive media offer similar but more complex challenges. We have chosen to concentrate on these in this paper for several reasons. They are:

- Lack of sound scientific data on the image information content of archived silver-halide film content
- Unusual spatial detail characteristics, including microstructure, of past transmissive photographic processes (e.g. Autochrome, Dufaycolor)
- An apparent and unsupported trend to choose unusually high sampling frequencies (2500-4000 ppi) as a standard for archival film digitization

In addition to resolution limits, the structure of slides or negatives may result in a viewing experience that is unique to the class of material. In such cases, the requirements for digitization may require the ability to represent the unique aspects of the analog content, its artifactual value. We have taken two historic formats to explore this use case - Autochrome and Dufaycolor. Both formats present a unique viewing experience resulting from the microstructure based on the manufacturing process for each format.

The objective of this study is to demonstrate methodologies, preferably analytical ones, for establishing and verifying digital imaging requirements for scanning resolution of photographic negatives and slides. As described above, two use cases for digitizing slides and negatives will be studied. They are-

A - Image information - The digital image is required to capture the full image information content of the original scene or object captured in the original photographic image. In this use case, increased resolution requirements for the digital image will not yield any additional detail about the scene or object that was photographed.

There is a belief that large format B&W negatives require high sampling frequencies because they have such a wealth of information in them. This information however is actually spread across a very large format with concomitant low image information per unit area on the negative. It is this packing density that determines required sampling frequencies (i.e., ppi). There is anecdotal conjecture by optical engineers that while the film itself was capable of high resolution, the lenses in the cameras used through the first half of the 20th century were not really that good and acted to limit the effective resolution of film images from those times.

B - Artifactual information - The digital image is required to capture the qualities of the negative or slide that is responsible for the characteristic qualities of the particular medium. An example of this is the Autochrome color process, where the size and distribution of the dye granules result in a photographic image with a visual quality similar to a pointillist painting. The requirements for this use case are independent of the requirements for capturing scene detail as in the use case described above.

Experimental Approach

There are four primary components to this study. They are:

- Media selection
- Measurement device calibration
- Data collection
- Data analysis and discussion

These items are serial in nature. Details of each follow.

Media Selection

To limit the scope yet create the most benefit, only first generation transmissive media intended for pictorial purposes was considered. While no color negative materials or microfilm were included, the analytical methodologies outlined in this paper for determining resolution levels can also be used for these materials. The largest portion of the materials considered was B&W silver-halide negatives created throughout the 19th century. The authors attempted to sample from a wide variety of formats. These included 35 mm through 8x10 formats.

Exploratory research was also done on media from two non-traditional transmissive media types, specifically Autochrome and Dufaycolor imaging processes. These were chosen because of their unusual microstructure and the way this structure can be discriminated from true image content information.

Measurement Device Calibration

All measurements of image detail and microstructure of the photographic originals were made with a Meiji MT8000 microscope with 20x and 50x plan objectives, equipped with a ProgRes C5 - 5.0 Megapixel CCD Camera used to capture illustrative images and for indirect measurements. Direct visual measurements were conducted using Mitutoyo Digimatic Series 164 Micrometer Heads, having an accuracy of 0.00015″ for XY stage movements.

The calibration of the ProgRes camera for all objectives was done using variable frequency glass Ronchi Rulings (5 lp/mm to 200 lp/mm). Calibration measurements were taken across a series of line pairs using the camera live view, taking four readings for each objective. The measurements were then verified by taking a direct measurement with the stage micrometer to prevent any gross errors that could be made by mistaking the ruling frequency. Calibration of the microscope/camera was performed monthly. The objectives were also calibrated immediately prior to making the measurements used in this study.

In order to establish resolution requirements, a calibrated device is required to accurately measure resolution. To demonstrate the viability of our approach, we chose two commercial off-the-shelf (COTS) transmissive scan devices. One was a Kodak iQsmart3 scanner at the U.S. National Archives at College Park. The other was a BetterLight camera/scanner at UC Berkeley. Both were calibrated using a film target that had been previously established suitable for accuracy to 10000 ppi and is often used for validating microfilm scanner performance. It is pictured in Fig. 1.

The true optical resolution of the cited scanners was determined through SFR analysis as described in ISO 16067-2 using slanted edge Spatial Frequency Response (SFR) protocols. The Kodak iQsmart scanner was generally used in the 3500-4000 ppi range. Measurements confirmed that it provided true optical resolution at whatever sampling frequency was selected, up to 5000 ppi. This level of resolution is more than sufficient for capturing the information and microstructure of historic images on transmissive media.

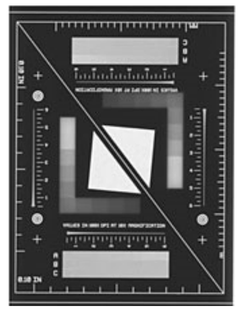

Figure 1. *Transmission Scanner Resolution Calibration*

The authors realize that high-end devices like the Kodak iQsmart3 scanner are often unavailable to most users (this scanner and similar models have been discontinued). To that end we also used a BetterLight scan back to demonstrate the use of typically available equipment in performing the characterization techniques described in this paper. Unlike the flatbed technology used in the Kodak iQsmart, the BetterLight was mounted on a copystand with a backlight illuminator. This parallel portion of the study was done at UC Berkeley's Moffitt Library by a staff photographer. Using a 50 mm lens, a true 4464 ppi was achievable. Several lenses were tried in order to achieve this level of performance

Example SFRs of the scanner's used in this study are shown in Fig. 2. SFRs from both scanners were very well behaved and reflected the true optical resolution of the selected sampling frequency. These SFRs were then used as scanner correction factors to determine the spatial information content in any selected negative. The way the data was selected from the negatives to determine this is described next.

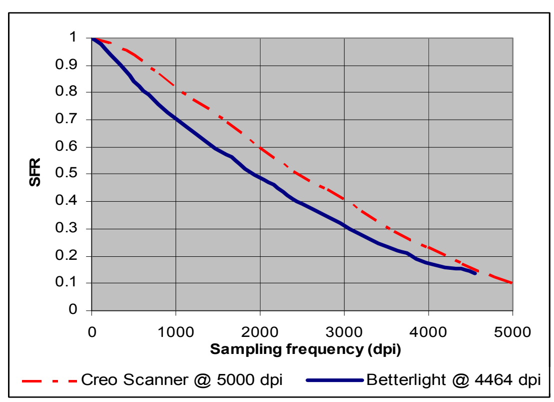

Figure 2. SFRs for scanners used in this study

Data Collection

Image data for calculating the information content for B&W negatives was gathered by selecting edge content from several areas on high-resolution digital images scanned directly from the original negatives. Two examples of this are shown in Fig. 3 and Fig. 4 (next page). This technique uses the same edge gradient protocols that are used for calculating a scanner's SFR. The interpretation of the results is slightly different however.

The SFR for a scanner itself reveals the extent to which contrast is reduced as detail content is increased. Using the calibrated target artifact shown in Fig. 1, the scanner SFR is calculated and through it, one can gauge the extent to which a selected scanner can reliably measure the detail content, or spatial information, of transmissive media. A known target standard was used to calculate the previously unknown scanner resolution. As long as the scanner's SFR significantly exceeds the expected spatial frequency content of the image information of the content under study, the scanner can be used as a measurement instrument.

We have borrowed a technique from the reconnaissance imaging community to analytically gauge the image information content of transmissive image content by reversing the process described above. By now knowing the scanner's SFR characteristics one can reverse the scanner calibration process to determine the amount of true image resolution, or information content in a scanned object, in his case, film. This is done by identifying naturally ideal edges in image content and using them as in situ imaging targets in their own right. For instance, the edges from digitized film content of Fig. 3 are from shadows of nearby objects and corner features of buildings. When photographed at long distances, these naturally occurring features can be considered near ideal edges that can be used to calculate the maximum amount of image information on the imaged object.

The edge data for calculating this information was gathered by identifying slanted edge content consistent with such natural features. While selecting these features does take some art, using only those with the highest calculated resolution insures against underestimating the image information content. In many ways it can be considered a maximum culling process.

Data Analysis and Discussion

Overview

All negatives and slides have an underling structure that is unique to the photographic process. Generally, this microstructure is not obvious, and when it is apparent, it is generally disparaged as unwanted image "grain" or "pixilation." While much of photographic history has been involved with minimizing the viewers' recognition of any underlying structure, microstructure is a distinguishing feature of historic interest and importance; and has a beauty of its own. And, although there are many aspects of artifactual information, in this paper we concentrate on technology-dependent microstructure as the quality of interest.

In the modern world of digital sounds and images, it's difficult to conceive of information in any other terms – even for those involved in imaging historic materials, we generally only view the magnified images in digital form and the ultimate detail of any image is the pixel. When the goal of imaging is capture of artifactual information, it is important to recognize that there is no absolute resolving frequency that represents the totality of an object. As opposed to the discussion in the first part of this paper, there are no algorithms to completely describe the features of a dye cloud, film grain, or the lines in the reseau *(*matrix) of a screen plate. Under the microscope, the structure of a negative or slide is composed of finer and finer detail, limited only by the optical limits of the device.

B&W Negatives

Once several edge features for a particular image were selected, the spatial frequency content of each region was calculated with the same edge gradient analysis used for SFR analysis. The maximum image resolution for each region was estimated by selecting the spatial frequency associated with the 10% response level from each region. An example of this for the six different regions of the image of Fig. 4 is shown below in Fig. 5.

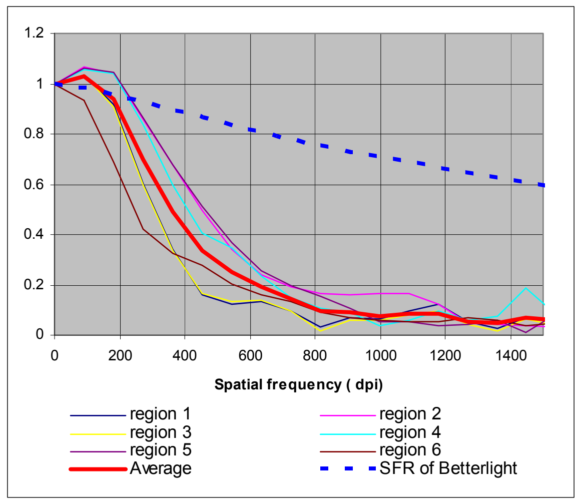

Figure 5 . *Spatial frequency content of image information in Fig 4*

The bold plot of Fig. 5 is the average of six different edge feature regions from Fig. 4. After correcting for the response of the BetterLight scanner (dashed line), the average 10% level, an indication of limiting resolution for this sample, is approximately 800 ppi for this image, no more. This then can be considered the maximum image detail of this negative. Can this then be considered the required resolution setting for a scanner digitizing such an item?

If scanners were perfect capture devices the cited resolution would be appropriate. But even the best scanners have some level of performance degradation. To account for this, we suggest that the 10% SFR level for any candidate scanner be at least 50% greater than the objective sampling frequencies of the actual image content. For the example of Fig. 5, this means that a scanner chosen to faithfully digitize the maximum image content should have an SFR level of at least 10% at about 1200 ppi.

While some may consider this unexpectedly low for film content the objective approach we offer here supports this conclusion, as does the detailed images of Fig. 6. We emphasize however, that this conclusion is made only for the specific collection content chosen. Given that this content was from a 1906 8" x 10" glass plate negative it is reasonable to conclude that the

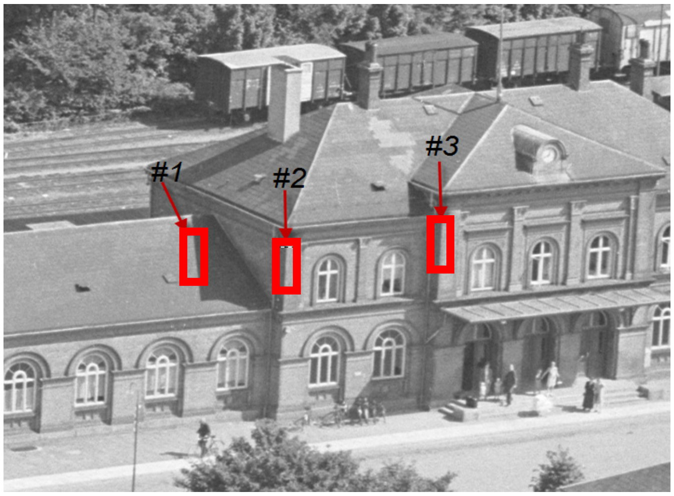

Figure 3*.* *Naturally occurring shadow and edifice corner features used to gauge image information content (4" x 5" aerial negative, Danish Royal Library)*

Figure 4*.* *Edge features used to calculate maximum image information content (8 x 10 glass plate ca 1906, Bancroft Library, UC Berkeley)*

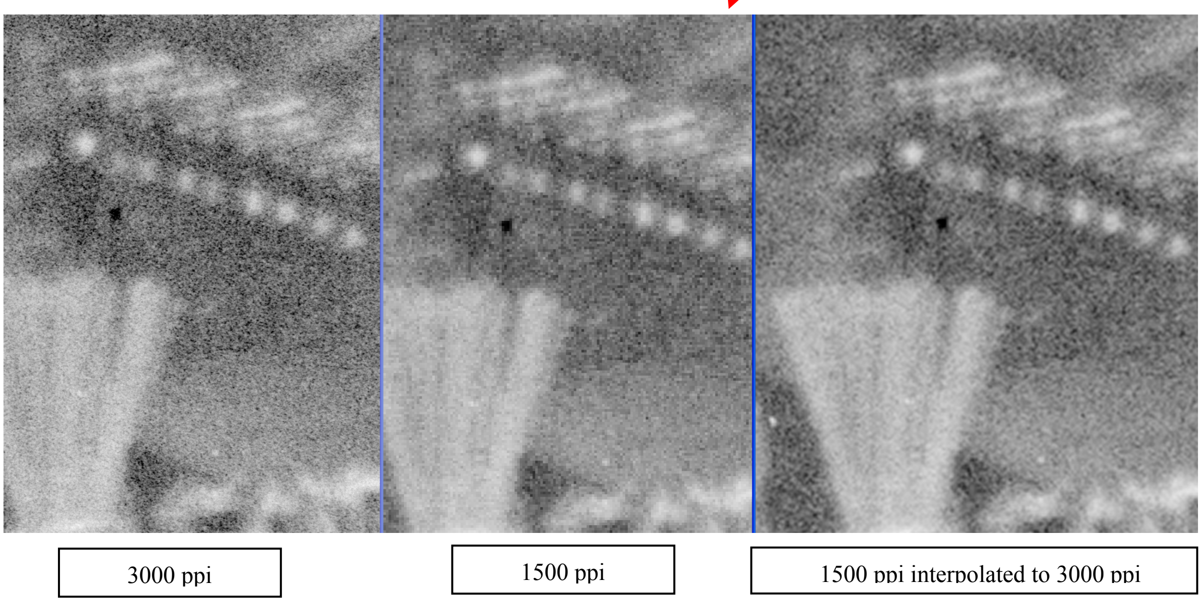

Figure 6. *Enlarged detail version extracted from the image of Fig. 4 showing no difference in image information*

information density would not be as good as expected with modern optical technologies. Take, for example, the image of Fig. 7: a 4x5 film negative ca. 1966.

Clearly optical and film technology had progressed over the intervening 60 years compared to the 1906 glass plate cited above. The edge feature responses for it are shown in Fig. 8. Notice that the measured information using the 10% criterion is significantly higher than that of the early 20th century glass plate; approximately 2000 ppi compared to 800 ppi.

Figure 7. *4 x 5 film negative, ca. 1966*

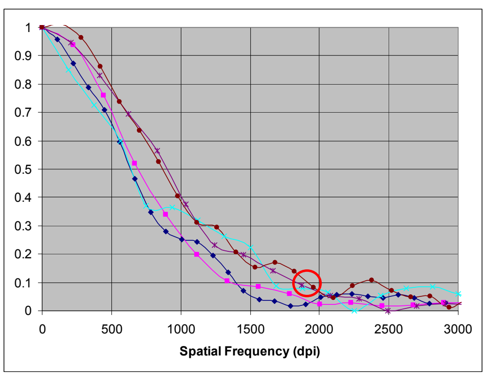

Figure 8 *. Spatial frequency content of image information in Fig.7*

Historic Color Originals

In this study, we looked at two color screen processes – Autochrome and Dufaycolor. Like other processes of the era (around the turn of the 20th century), Autochrome and Dufaycolor are additive color methods, depending on three primary colors comprising a screen that lies over a panchromatic emulsion. The technique is essentially the same as what is employed in modern digital cameras, where a color filter array (CFA) lies over the camera sensor.

These two processes were chosen for both their historic importance and their widely divergent characteristics. Autochromes have a random distribution of color elements that are roughly circular, while the Dufaycolor has a geometric (grid) structure more characteristic of photographic screen processes. To describe the characteristics of the images resulting from these processes, it is necessary to provide a brief description of each along with the more detailed information on their microstructure.

The Autochrome plates were manufactured by first creating potato granules ranging from 10 to 20 microns in diameter. These granules were dyed red-orange, green, and violet. The colored granules were mixed and then dusted on a glass plate, forming a single layer of composed of a random distribution of colors. The spaces between the granules are filled with a fine powder of carbon black. Our studies of Autochrome structure found a high degree of consistency in the granule size and spacing across the area of a plate, as well as across samples. If the granule size is estimated to be an average diameter of 15 microns, with granules assumed to be touching, there will be approximately 1,700 granules/inch ($15\mu m = 5.9 * 10^{-4}$ inches). Although an assumption there will be no space between granules may seem unrealistic, samples from various plates shows this to be a fair approximation as show in Fig. 9. This agrees with studies done at the Bureau of Standards, where their measure was 1666 granules per inch [1], and with Louis Lumiere's report that "… the starch granules touch one another …" when applied on the plate [2]. Approximating the scanning frequency as 1.5 times the highest frequency of the source image, yields a scanning resolution of approximately 2500 ppi to capture the microstructure of an Autochrome image.

The problem arises in attempting to reconcile the estimated 1700 ppi in Autochrome plates with widely recognized pointillist nature an Autochrome image. The impression of a colorful grainy quality is clearly evident at a magnification of 4x. This disparity has been generally been described in the literature as being the result of grouping of grains of like color – a statistical inevitability in a random distribution of three colors. In searching the literature, we were unable to find any formal studies to investigate a correlation between color grouping and the impression of color grain described above.

While the primary concentration here is on the unique visual qualities of Autochrome, it is worth noting the resolving capabilities of typical Autochrome images. In contrast to the negative B&W images examined earlier in this paper, the image resolution of Autochromes is very close to the basic structural elements – the starch granules.

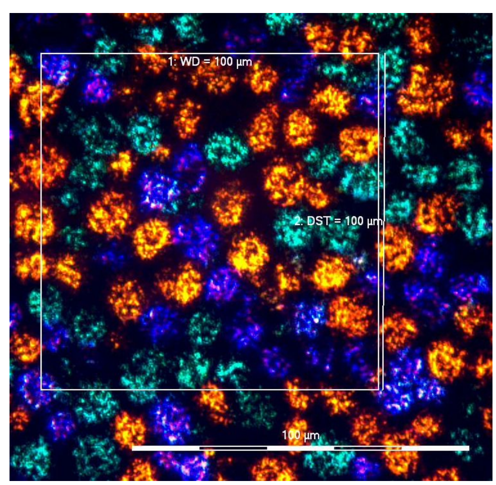

Figure 9 *. Measurement of starch granules from an Autochrome*

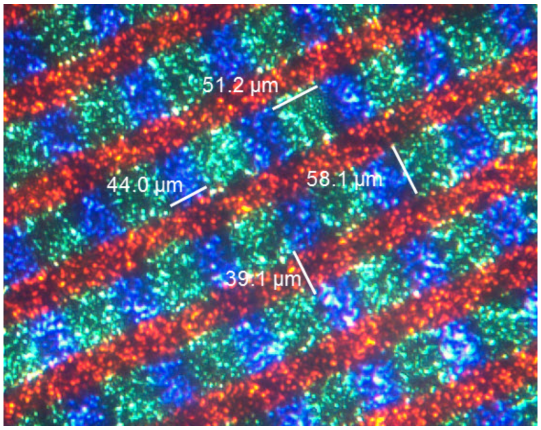

Figure 10 *. Measurements of the screen components of a Dufaycolor*

The Dufaycolor was a screen process composed of grid containing diagonal blue and green lines that are parallel, with perpendicular red lines as seen in Fig. 10. The manufacturing process is composed of six steps, starting with a uniform layer of a blue dye that acts as a resist, printed with green ink, then bleached, then repeated for red. An excellent illustration of the process can be found in *The Dufaycolor Manual* [3]. Our studies have found these lines varying across plates from approximately 40 microns through 60 microns, with the red line typically more narrow than the green or blue. A typical example is shown in Fig. 10. The literature from the time Dufaycolor was manufactured describes the lines being 500 per inch [4] [5], or 50.8 microns. Using the same factor as used throughout this paper, we can estimate the appropriate scanning resolution as being 1.5 times 500 lines per inch, yielding a value of 750 ppi.

Unlike with the Autochrome process, the structure of a Dufaycolor becomes visually apparent at a higher magnification than expected based on the dimensions of the elements of the microstructure. This is primarily of function of the small variance in the luminance between lines that are adjacent to each other; the primary difference being the chrominance. Converting the digital images of Autochrome and Dufaycolor to grayscale, Fig. 11, illustrates the clear difference in the perception of the features of the two microstructures.

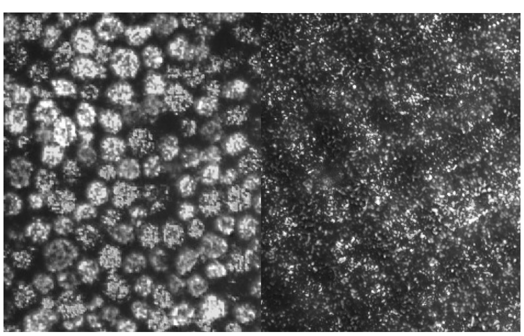

Figure 11 *. Grayscale comparison of the microstructures of an Autochrome (left) with a Dufaycolor (right)*

While the description and example of luminance vs. chrominance for Dufaycolor generally holds, it should be noted that examples of Dufaycolor images can be found where there is a marked difference in the luminance between the lines in the screen compared this example. Although we have not conducted tests on a sufficient number of samples to report on the distribution of luminance deltas in scenes, and where the greatest deltas occur, our limited number of samples indicates the maximum occurs where there are man-made colors such as paints or dyes.

Conclusions

While our objective was to demonstrate a methodology for taking direct measures of samples or those available in the literature to extrapolate required resolutions, we found the path from measures to perception to be more complex than we imagined. Our results describe some of the complexities as well as suggesting future areas of further research.

For transmissive photographic originals, we believe it is appropriate to determine scanning resolution requirements based on two different use cases – first, an approach based on the informational content of the image and, second, an approach based on the artifactual content or microstructure of the original.

Current scanning recommendations tend to overstate the need for uniformly high spatial resolutions requirements for many historic transmissive originals. Our research indicates capturing all the informational content is achieved at comparatively lower spatial resolution for originals like older B&W film negatives, but is not as feasible an approach for early color screen processes due to the complex nature of the image structure.

For B&W negatives, it is possible to determine the amount of image resolution or informational content of a photograph using an edge gradient analysis of appropriate image features on high-resolution digital images scanned from the originals. This technique shows significant differences in the amount of informational content in B&W negatives produced over time, as both photographic and optical technologies improved. For many B&W film negatives produced during the first half of the 20th century, our analysis indicates a scanning resolution of 1200 ppi to 1500 ppi will reproduce the informational content of the original negatives. While B&W negatives from the latter half of the 20th century typically have a significantly higher level of informational content, and a scanning resolution of up to 2800 ppi would be appropriate for certain negatives.

Determining the relationship between microstructure and the unique visual perceptions of early color processes, like Autochromes and Dufaycolor, is a complicated affair. In the case of Dufaycolor, it is a functional matter of screen pattern, size and microdetail being delineated by chrominance. The perception of the image characteristics for Autochromes, however, is a less well understood process – making it difficult to conclude the appropriate scanning resolution to capture the "informational content" of an Autochrome. We found various conjectures on what leads to the unique pointillist qualities of an Autochrome image, we were not able to find any literature documenting formal studies on the topic. Our analysis indicates a 2500 ppi scanning resolution is needed to capture the artifactual aspects or microstructure of an Autochrome image, while a minimum of only 750 ppi is needed for Dufaycolor images. We have suggested some tests to explore one theory of the correlation between microstructure and these perceptual qualities, but we would like to see a comprehensive study. Future studies to explain the phenomenon might include investigation in the following areas - statistical distribution of colors, size of color groups, and luminance minus chrominance.

Acknowledgements

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[4] Ibid., 2
[5] Friedman, *History of Color Photography*, 141-142
[7] Friedman, *History of Color Photography*, 139

Author Biographies

Don Williams is founder of Image Science Associates, a digital imaging consulting and software group. Their work focuses on education, standards, and tools for the cultural heritage imaging community. He has taught short courses for many years, contributes to several imaging standards activities, and is a member of the Advisory Board for the interagency US Federal Agencies Digitization Guidelines Initiative, FADGI

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Steven Puglia is a Digital Conversion Services Manager at the Library of Congress. Previously he worked as a Preservation and Imaging Specialist at the US National Archives and Records Administration for over 22 years. He coordinates the Still Imaging Working Group of the Federal Agencies Digitization Guidelines Initiative