Report to

LIBRARY OF CONGRESS

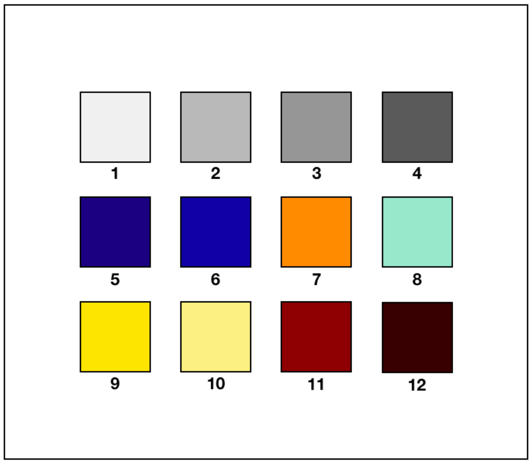
FADGI Color Consultation services

Report on:

Research of imaging prior art and best practice related to human visual perception and transmissive digitization;

and

Creation of prototype spectral based transmissive calibration target, and an appropriate methodology to implement their use in a FADGI compliant digitization program



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Executive Summary

In support of the digitization efforts of the Library of Congress, a contract, *FADGI Color Consultation services*, was awarded to Avian Rochester, LLC for research, reporting, and improvement of the spectral imaging capabilities of the Library. This contract was effective as of June 6, 2018, and all task are to be completed 320 days after that.

This report fulfils the requirements of Task C.3.2 of the project, which is to report the effort performed for Task C.3.1, *Research into imaging prior art and best practice related to human visual perception and transmissive digitization*. With the delivery of five physical targets, the description of their use enclosed herein also completes Task C.3.3, *Creation of 5 prototype spectral based transmissive calibration targets for use with the FAGDGI program, and an appropriate methodology to implement their use in a FADGI compliant digitization program*.

After reviewing the general requirements for imaging transmissive materials, the state of the art at the Library of Congress is presented. The current practice is limited to the use of the IT/8 family of film-based scanner characterization targets. This may be sufficient for certain cultural heritage scanning applications, but it not suitable for the general case. The literature offers some improved solutions, but again these are not likely suitable given the requirements of general transmissive imaging.

The fully general case for transmissive or reflective imaging is a spectral approach, where the sample spectral transmittance (or reflectance) is predicted for every pixel in a given image. Some potential technologies for spectral imaging are mentioned, followed by the advantaged of such an approach.

The final section describes the new physical transmissive target provided as a part of the current contract. The use of the target is also described.

Introduction

Pressure to increase productivity of digitization activities in the archiving community has forced the evaluation of all aspects of the calibration, processing, storage, and transmission of imaging data. The Library of Congress (LC) strives to be at the forefront of the field. One important aspect of the imaging made at LC is transmissive imaging. Previous reports have discussed the color calibration of reflective systems, and this report will follow with the same philosophy when applied to the imaging of transmissive materials. As with the reflective research, current systems create RGB digital output files which are then converted to colorimetric coordinates using profiling tools. Further, and again as applied in the reflective approach, the goal is also to move the LC systems towards a spectral imaging workflow. The imaging and profiling systems currently applied fall short of the accuracy requirements for color capture and the production of spectral output. Put most simply, when the captured images are processed and viewed on a display, the colors do not sufficiently match the colors of the original artifact.

The balance of this report will: discuss the requirements for a transmissive calibration target; examine the current practices at LC; and then explore the state of the art in the literature; describe the physical targets being delivered as a part of this contract; and describe the use of the physical targets within a current FADGI workflow. The goal of this report will be to provide an understanding of how well current LC practices compare to what is currently available in the field, and identify possibly areas of improvement. This research will lead into the description and use of a prototype transmissive target for future evaluation using LC transmissive imaging systems.

Requirements for Transmissive Reference Materials

The most fundamental requirement for any reference material is that it be configured in a way such that it can be measured in a like fashion on both the reference and the test instruments. For the case of the filters describe herein, this is met by virtue of being flat filters of uniform thickness, and large enough for accurate measurements in the reference instrument at Avian Rochester, LLC.

The next set of requirements center on making sure that the test measurements of the filters are consistent over time:

- *Temporal Stability*. When properly handled and maintained, filters should not change color with time. The target holder (described below) is configured to allow recalibration on the Avian Rochester, LLC reference instrument in the future, if needed.
- *Thermochromism*. Most materials change color with temperature, it is helpful to either limit this color change by performing the test measurements at the same temperature as the reference measurements were made. Barring that, an analysis could be performed to determine the color change as a function of temperature, and apply the resulting transform to the test data.†
- *Angular uniformity*. Filters transmittance should be the same regardless of the incident angle of the light. In practice this is not possible to achieve with flat filters, but the effect can be mitigated by avoiding interference filters. Figure 1 schematically shows the types of spectral transmittance change for a few incident angles. due to a 5°, 10°, and 15° change in incident light for interference filters (left) and absorption filters (right). In general, the effect in interference filters will change the wavelength of the peak, while in absorption filters it will change the height of the peak. The interference example will show a color shift, possibly a marked one.
- *Spectral Distribution*. The filters should cover a good spectral range, both in height (transmittance) and wavelength. Spectral transitions should be distributed across the useful wavelengths.
- *Robustness*. The filters should be able to be lightly cleaned without changing their transmittance.

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† At this time it is assumed that the temperature of the reference and test measurements will be similar enough to avoid any unreasonable effects of thermochromism.

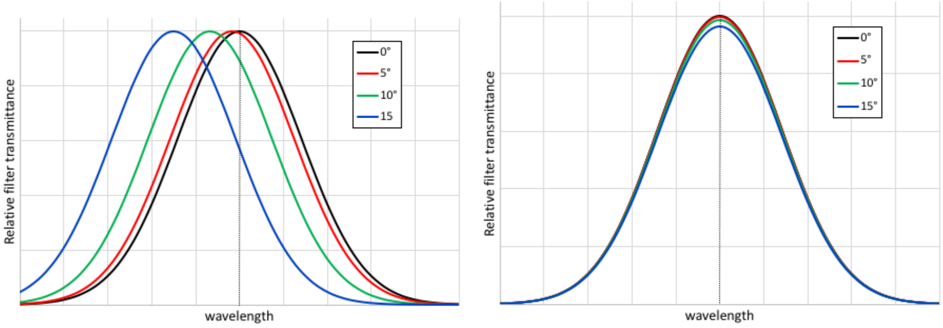

Figure 1. Representative types of spectral transmittance change for a few incident angles for interference filters (left) and absorption filters (right).

State of the Art at Library of Congress

The current practice at the Library of Congress [1] relies on the use of IT/8 family of film based targets. Using these targets, and their associated reference measurements, scanner profiles are generated using BasICColor Input v5 or other off-the-shelf tools. The result is an ICC profile which, when applied to a given scanner image, allows the sample to be rendered for display. These tools and targets are the standard for the industry, and more thoroughly described below in the more general section on "State of the Art in the Literature."

The IT/8 is printed on standard film, and therefore contains three dyes (cyan, magenta, and yellow). After scanning the IT/8 on the scanner, the image is processed using BasICColor Input v5 [2] and the reference data for the target. Current practice at the Library is to rely on manufacturer's data for the IT/8 targets. This is necessary because the Library lacks the capability for small area transmittance measurements. (IT/8 patches are only a few mm across.)

While these current practices were arrived at from a logical historical progression, and are largely in line with the state of the art, there are some shortfalls that can be addressed. First is the fact that the film based IT/8 targets have only three dyes. This results in a very limited spectral diversity, and ultimately leads to accurate profiles only when the samples to be imaged were created from the same film base as the reference IT/8. A degenerate solution to this limitation would be to have IT/8 targets made from every film type that needs to be imaged. Even this procedure will be insufficient because it will not account for aging and fading of the sample, which invalidates the profile.

The second shortfall is regarding the accuracy of the reference data. Only with accurate reference data can one expect to create accurate profiles, and which will be applied to render accurate images from the scanned samples. The use of manufacturer's data is limited for two reasons: 1) it is not typically measured from a specific IT/8. That is, the data are representative of an average target, but not necessarily accurate for any particular target. And 2) even if the data were initially accurate, there is no way to account for the inevitable fading of the target, which will invalidate any profiles created from a new (unfaded) target.

State of the Art in the Literature

Reference 3 provides a solid, if a bit dated, framework for characterizing digital scanners. While the technology has advanced since that article was published, many of the mathematical techniques are still valid. Some of these details are below the threshold of interest for the Library of Congress applications, since they assume more direct involvement in the mathematics of developing the scanner profile, whereas Library processes generally depend on commercial profiling software (eg: BasICColor).

The models to profile transmissive devices are not in principle different from those used for reflective media. For completeness these will be briefly reviewed here.

The goal is to relate linearized scanner coordinates with color coordinates, typically XYZ tristimulus values. Scanner coordinates may already be linear with respect to tristimulus values, but that should be verified by examining the scanner output for a series of neutral input patches. By plotting the scanner coordinates against the input Y tristimulus value, the decision can be made as to the linearity. If there is a noticeable curve ("gamma") in that plot, it must be modeled and the inverse transform applied to all scanner data before subsequent processing. Note that camera raw data are usually (and properly) assumed to be linearized.

With linear scanner coordinates, here assumed to be R, G, B, the simplest transform to XYZ is a 3x3 matrix:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ b_{21} & b_{22} & b_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \qquad (1)$$

A more complex model can be applied that uses polynomial or other terms. In general these should not be needed for linear data, with the exception of an offset. The forward form of that model is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ e_{21} & e_{22} & e_{23} & e_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix},$$

Where the terms $d_{14}, e_{24},$ and f_{34} are the offset terms for R, G, and B, respectively. More complex models are beyond the scope of this report, but can be found in reference 3. From XYZ the usual color coordinates can be calculated (CIELAB) from which color differences can be calculated to verify model performance.

Techniques have been developed to predict sample spectral data when certain assumptions are made regarding the samples. Berns & Shyu [4] determined that if the spectra of the samples are known, and of limited spectral shapes (as present in three-color film) the RGB scanner coordinates can accurately predict the spectra of each pixel. While the idea of predicting spectral data from an RGB scanner may be appealing, there are some significant limiting factors to the application of this technique. For example, different file types require different characterization models. Further, faded film of a given type will need a different characterization model than new film of the same type. For these reasons this technique is not suitable for application at the Library. Subsequent works based on similar techniques (see for example reference 3) all suffer from the same limitations.

Hardware Considerations for a Spectral Approach

The procedure described above (summarizing reference 4) relates the use of the target to spectral imaging. In the case above, the transmittance spectra are inferred from the RGB channels of the scanner after characterization. While this procedure is useful for certain situations and samples, in general it will be cumbersome to implement for general spectral imaging of transmissive materials. Alternative approaches have been proposed in the literature. These techniques are often applied for reflective samples, but there is no technical reason why they are not also applicable to transmissive measurements.

With respect to spectral imaging, the limitation of RGB scanners is that they do not produce enough data. The three RGB channels cannot hope capture the variations that are often present in the spectral properties of interesting materials. Therefore a technique must be applied that captures more channels than three. Some of what follows was provided in more detail in a previous report [5] to the Library of Congress.

Abridged Approaches

The Two-filter approach [6] was summarized in reference 5. It can produce limited spectral data, but is better suited to produce highly accurate colorimetry. It effectively produces five independent channels (image planes) and so remains on the side of color imaging rather than spectral imaging.

Full Spectral Capture

The use of a liquid crystal tunable filter (LCTF) was also summarized in reference 5. While the spectral imaging capabilities are reasonable, this method suffers from two shortfalls that make it impractical to recommend: it is quite slow, and the channels are created by interference filters, which have serious directionality problems (the spectral shape of the transmittance curve change with the angle of incident light).

Another full spectral capture technique relies on individual filters for each wavelength band, eg: 400nm to 700, sampled every 10nm. As implemented (in spot instruments, not to the knowledge of the author in any imaging devices) these are also interference filters. If 31 (or more) suitable filters could be designed, the system would still require 31 (or more) exposures per spectral capture.

It is important to consider that any filter device has the possibility of misregistration between the image planes. Any time a wheel is moved or other physical adjustment is made, the possibility exists for the camera to move, however slight that movement might be. Therefore a registration step must be included in the image processing path.

Partial Spectral Capture

A possible solution lies between three channel RGB systems and 31 channel full spectral systems. The literature describes systems with 7 or more channels which, with proper processing, have been shown to produce accurate spectra. These techniques are based on sequential exposures using a monochrome imaging detector. The spectral differentiation is created using a series of filters over a white light source, or a series of tuned light sources (eg: LEDs). The shortfalls of the multi-filter design have been described. A system using multiple sources need not have any moving parts that will require registration of the image channels. A system using this approach this is available for commercial purchase [7]. In addition to avoiding the problems described with interference filters. Sequential illumination can take place very quickly since there need be no moving parts. The sequential pulsing need not take longer than the individual exposure time for each channel, and whatever time it takes for the camera to be prepared for the next exposure (primarily waiting for the transfer of the image data).

These systems are described as “partial spectral capture” because the number of channels is usually fewer than those measured by a spectrophotometer. There is no reason why this need be the case, it is simply a matter of logistics. However, and analysis should be made to determine the optimum number of channels, and their spectral makeup, for the application of cultural heritage and its unique challenges.

Benefits of a Spectral Approach

The true material properties, transmissive or reflective, cannot be described completely using any colorimetric capture system. Any colorimetric data are useful only for specific viewing conditions. That is, a set of CIELAB measurements will accurately correlate to human perception only when the objects represented by the CIELAB data are viewed under the same conditions for which the CIELAB data were rendered. If the object are viewed under different conditions, most commonly by changing the light source, the perceived color can change, sometimes dramatically. However, if the spectral properties of the object are known, the appropriate CIELAB can be rendered for any desired light source.

The ability to render perceived color under any viewing conditions has important implications for the museum field. Consider the advantages to a curator, who can evaluate any lighting of an artifact virtually. An exhibit that might have multiple lighting environments over time, perhaps daylight through skylights, and indoor illumination at night, can be accurately modeled and viewed in softcopy, without any need to set up actual lighting, or physically arrange potentially priceless works of art or cultural heritage.

Description of the Target

The physical target consists of a 7.5” by 6.5” x 0.125” aluminum frame holding 12 1”x1” colored filters. A schematic is shown below in Figure 2.

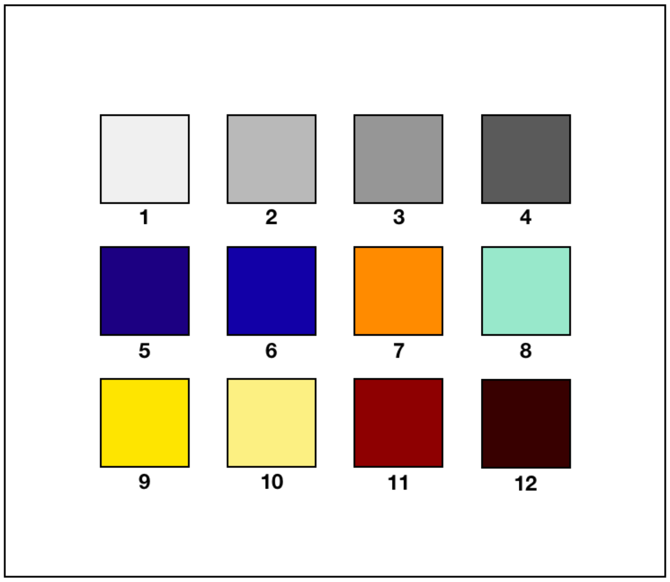

Figure 2. Schematic of the physical transmittance calibration target. Note that colors are representative only.

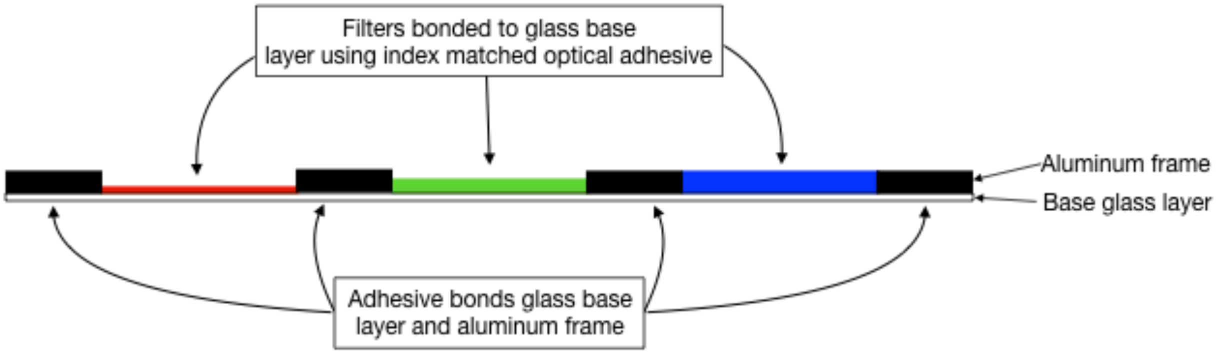

Figure 3. Cross sectional schematic of target. Note that filters are of various thicknesses, but all are optically bonded to the base glass layer. The measured data accompanying the target accounts to the base layer transmittance.

The filters are all Schott (or similar) absorption filters. Their thickness varies due to the availability. The thickness variations should have no effect on the use for the given applications. The spectral and b* vs a* plots are shown in Figure 4.

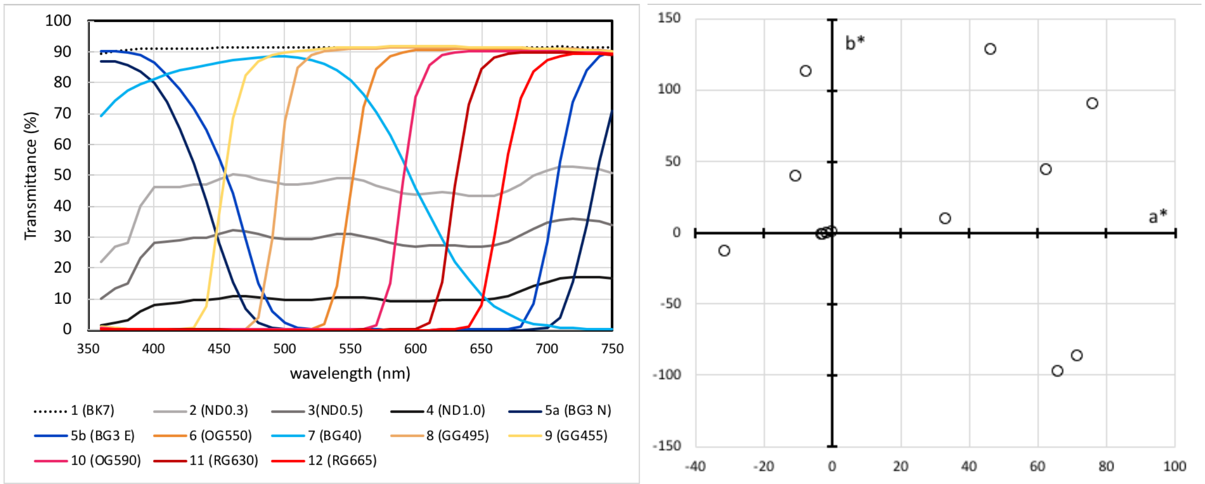

Figure 4. Spectral transmittance (left) and b* vs a* (right) for the 12 filters in the physical target.

Regarding the distribution in the b* vs a* plot, there does appear to be a gap in the lower central region of color space. This is an artifact of the spectral selection process for the target filters. The goal for that process is to distribute spectral transitions across the visible wavelength range. The number of available filters with useful transitions in the 400-500nm wavelength range is limited; the family of long-pass yellow and reds are much more readily available. Note that the BG3 spectra curves are transmissive above 700nm, as seen by the sharp rise of the rightmost curves (blue and black) in Figure 4.

In Figure 4, there are two entries for BG3 filter (labeled 5a and 5b). The difference between these is the filter thickness; only two physical filters were available, each starting in the 2”x2” square format. Cutting, this yielded four 1mm and four 2mm thick filters. To populate five complete targets, two of the 1mm will be cemented together to make a single 2mm filter. This will have a slightly different transmittance, which will be provided with the other spectral data upon delivery. The “odd” target will be clearly marked to avoid confusion in the imaging labs.

Most importantly, we note that this target is a prototype,. As such it is delivered with the expectation that improvements will be made before it is put into general use. These improvements will likely involve: adjusting the filter set and/or adjusting the physical configuration (size and/or location of the filters). An initial testing and analysis by Library personnel will set these improvements in motion, provided the work is covered in future contracts. Such analysis, based on current Library imaging hardware, should entail the traditional use described below, comparing the measured CIELAB with the CIELAB predicted after the ICC profile is applied to the camera data.

Use of the Target

The target should be used in the same fashion as the reflective targets. The target should be imaged with the test scanner, and the image should be combined with the reference color data to generate an ICC profile. As of this writing the primary software tool for this is BasICColor Input v5. [4] It is possible that a new template will need to be generated by Library personnel or those at basICColor GmbH. Once a profile is generated it should be used in the traditional method after being attached to scanned images, CIELAB or other color data are rendered.

We also note that basICColor now permits the use of spectral input data. The target will be provided with spectral transmittance data as well as D50/2° CIELAB. The use of the RGB scanner does not permit predicting spectral data without advanced modifications.

Approaches to Facilitate Spectral Imaging of Transmissive Samples

The literature contains some very relevant work that will permit the Library of Congress to proceed towards limited spectral transmittance imaging. The procedure is described in reference 4, and will be summarized here.

Given that the current Library scanners are generally three channels (red, green, and blue), it is not mathematically possible to estimate sample spectra for the general case. However, for the case of film scanning, the samples contain restricted spectral diversity, since the color is based on the mixture of only three dyes (typically cyan, magenta, and yellow). Detailed mathematics is in reference 2; the qualitative steps to be taken to derive the model are:

1. Measure the spectral transmittance of a large number of areas on a given sample. The locations of the measured regions must be recorded.
2. Convert the spectral transmittance to spectral density.
3. Perform principle component analysis on the spectral density data. This will yield three (spectral) eigenvectors. They will require some additional processing (eg: further fitting to the spectral data to ensure they are all positive). The result is the set of spectral densities in the equation below: $D_{\lambda,c}, D_{\lambda,m}, D_{\lambda,y}$.
4. Image the sample in transmissive mode (generating an RGB image).
5. Average the RGB data for each of the measured regions recorded in step 1.
6. Relate the image RGB coordinates to the spectral density scalars (below: c_c, c_m, c_y) by combining the spectral densities to minimize the difference between the predicted model transmittance and the measured transmittance from step 1. The relationship (most likely a 3x3 matrix, RGB to concentrations) defines the forward model, predicting the CMY density of each pixel in the RGB image.

The model described in reference 2 is:

$$\hat{T}_\lambda = T_{\lambda,g}\exp\left[-\left(c_c D_{\lambda,c} + c_m D_{\lambda,m} + c_y D_{\lambda,y}\right)\right]$$

The model may require other terms; this is the most basic form.

Conclusions

The current practices at the Library of Congress as well as those in the literature, are described for transmissive imaging. Besides the use of spectrally-limited film-based targets, the Library is not far from the recommended procedures in the literature. A prototype target has been described, along with its proposed usage.

However, the limitations in the procedure described herein (mostly that there is no *a priori* knowledge of the dye transmittance) mean the spectral oversampling and principle component analysis must be completed for each sample. At best, the measurements must be completed for each family of samples where there is confidence that their history is identical. Given the importance of more practical long term solution

References

[1] Thomas Rieger, personal communications, October 2018.

[2] BasICColor Input 5 software is provided by BasICColor GMBH. Refer to `<basiccolor.de/en/>`.

[3] Tony Johnson. "Characterizing colour scanners and digital cameras." *Displays* **16** No 4 (1996).

[4] Roy S. Berns and M. J. Shyu. "Colorimetric characterization of a desktop drum scanner using a spectral model." Journal of Electronic Imaging, **4**, pp364-372 (1995).

[5] David R. Wyble, "Report on research into spectral imaging prior art and best practice," dated January 2018.

[6] Francisco H. Imai and Roy S. Berns. "System and method for scene image acquisition and spectral estimation using a wide-band multi-channel image capture." United States Patent 7,554,586 (2009).

[7] See for example MegaVision imaging products at `www.mega-vision.com`.