

Beyond RGB 2.5: New features and improvements to a free, open-source spectral image processing software application

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Abstract

Differences between the human visual system and RGB cameras create challenges for the color-accurate reproduction of cultural heritage materials. Spectral imaging techniques can address these challenges but often require specialized equipment, training, and software, which can make implementation difficult. The purpose of Beyond RGB is to lower the barrier to entry by providing free, open-source, and user-friendly software for processing spectral imaging. Users input sets of 6-channel images formed from pairs of RGB images captured with a standard camera under two different conditions. Outputs include a color-managed TIFF, interactive spectral reflectance estimation for regions of interest, and reports detailing accuracy and performance. Version 2.5 of the software includes changes to the processing pipeline, new features, and improved usability and visualizations.

Introduction

Standard RGB cameras are prone to color errors due to differences between the spectral sensitivities of camera sensors and human photoreceptors. This is especially true for highly color-constant materials, which are frequently encountered in cultural heritage imaging [1]. Spectral imaging methods can address this issue by capturing more information about the material's spectral reflectance or transmittance. Unfortunately, spectral imaging typically requires specialized equipment, training, and software, making implementation difficult or impossible for many cultural heritage institutions.

Beyond RGB is a software that processes 6-channel images captured using the dual-RGB technique. Dual-RGB leverages the trichromatic nature of RGB cameras to quickly capture 3 channels simultaneously. By using a filter or adjusting the lighting between shots, two distinct 3-channel images can be combined into a 6-channel spectral image. Using color targets containing patches of known spectral reflectance, a transformation can be fitted to convert the 6 camera signals into XYZ values for the standard observer. This process is summarized in Figure 1. A broad overview of the topic is given in Berns' technical report [2]. It should be noted that using a standard RGB camera limits dual-RGB to the visible spectrum (unless the camera is modified – e.g., by removing the IR filter).

One of the primary advantages of dual-RGB is the use of standard equipment, including an RGB camera. This eliminates the need to purchase additional, expensive cameras that are typically required for spectral imaging. However, either filters or multiple light sources are necessary, which can be expensive. Research into low-cost alternatives is ongoing [3-4]. Another barrier is that 6-channel images cannot be processed by most image processing software, requiring users to either purchase specialized software or learn highly technical programs. Beyond RGB was built to address this issue.

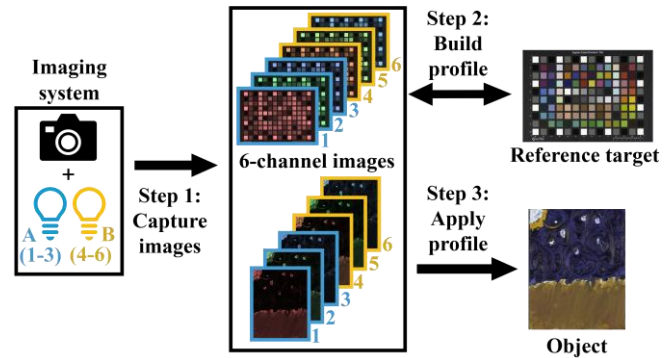


Figure 1. Overview of dual-RGB imaging. Lights are used to represent the two spectrally distinct conditions (A & B), but in practice, filters may also be used.

Beyond RGB Overview

Beyond RGB is a free, open-source software application for processing dual-RGB images. It applies custom profiles for colorimetric and spectral color-managed images, as well as supporting files containing accuracy reports and documentation of the process. An emphasis is placed on a user-friendly design that reduces the need for high-level expertise, encouraging the integration of spectral imaging as a routine method in cultural heritage institutions. The software can be downloaded from the [Beyond RGB website](#) [5], and the source code can be found on the [GitHub](#) [6].

To use the software, the user must input color target reflectance data and at least three pairs of raw images, captured under the two different conditions. These pairs include flat field, dark current, and color target images. The object may be included in the color target image or provided in a separate image. The flat field image is a capture of a white (or gray) board positioned in the same plane as the object. The dark current is captured with the lens cap on. The color target image must contain at least a calibration target and may also contain a verification target and/or an object. All images must be captured with the same camera settings. Software versions after 2.0 support uploading multiple object images for batch processing. Figure 2 provides an example of an input image set for Beyond RGB.

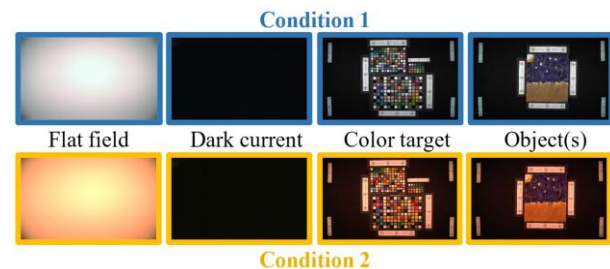


Figure 2. Example input image set.

The Beyond RGB pipeline can be described in three sections: pre-processing, processing, and output. Pre-processing steps are applied to the images to reduce the influence of imaging errors and prepare the data for calculations. Processing steps involve generating colorimetric and spectral profiles, which are then applied to the images. The output includes corrected images, supporting documentation, and interactive visualizations.

A simplified version of the processing pipeline is shown in Figure 3. Of particular interest are the bolded and italicized steps, indicating updates to version 2.5, which will be discussed in the following sections. Details about the pre-existing steps from earlier versions of the software have been previously published [7-9].

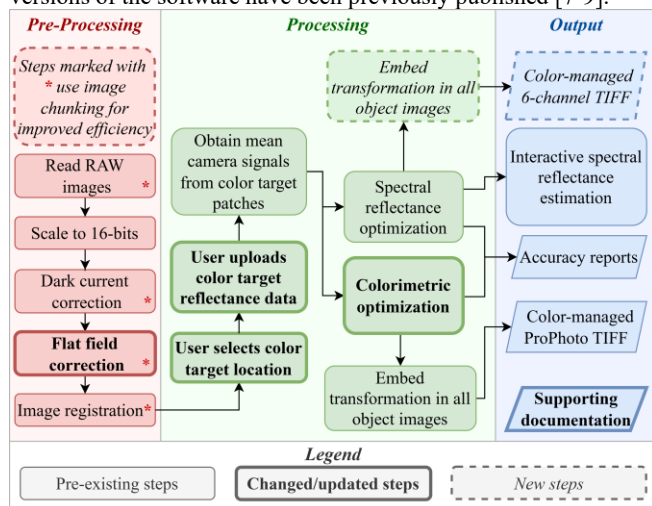


Figure 3. Summary of the Beyond RGB pipeline. Bolded steps indicate updates or changes to version 2.5. Italic steps indicate new features.

Updates to Beyond RGB 2.5

Adjustments to the Image Processing

Some of the most significant updates in Beyond RGB 2.5 are the changes to the image processing algorithms. This includes changes to the general pre-processing pipeline, flat field correction, and colorimetric optimization.

Figures 4 and 5 show a comparison between the output images from Beyond RGB versions 2.2 and 2.5, respectively. A low-quality image was selected to highlight the noise reduction. Both images were processed using the same input image set and settings.

Applying a low-pass filter to the flat field images

To account for lighting fall-off caused by scene lighting and camera optics, Beyond RGB introduces a flat field correction in pre-processing (also known as even-fielding, or LCC). It requires an image of a flat white (or gray) board captured in the same position as the objects. The correction includes a pixel-wise division of the flatfield images from the color target and object images, and rescaling to account for the reflectance of the white board.

Version 2.5 applies a low-pass Gaussian filter to the flat field images before the pixel-wise division. This eliminates texture and random pixel-to-pixel variation in the flat field image, thereby reducing amplification of noise in the final images.

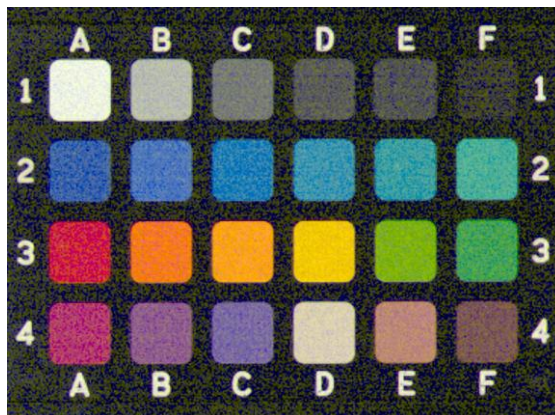


Figure 4. Close-up of a color target cropped from the color-managed output image from Beyond RGB 2.2.

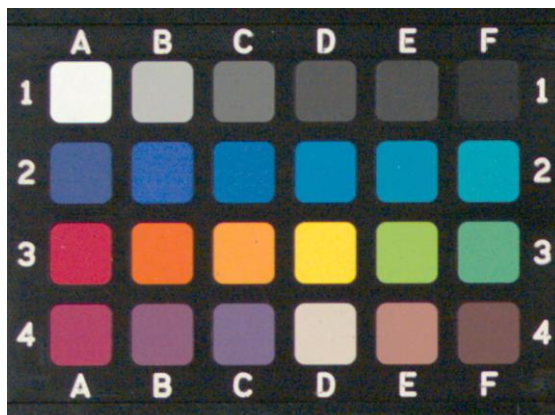


Figure 5. Close-up of a target cropped from the color-managed image output from Beyond RGB 2.5.

Noise penalty in the colorimetric optimization

Beyond RGB generates a color profile matrix through non-linear optimization. An initial matrix is used to convert the 6-channel camera signals into XYZ values using the 1931 standard observer. These are transformed into CIELab coordinates using illuminant D50 and compared against the reference CIELab values of the calibration target. The matrix is iteratively updated until the cost function is minimized.

Previously, the cost function for this optimization was simply the mean ΔE_{2000} of the calibration target patches. However, this method is known to be prone to significant noise propagation, leading to undesirable image artifacts and high noise sensitivity [10]. The dual-RGB method, in particular, is highly susceptible to noise propagation because of the high interdependence between channels (e.g., the first and second red channels), which often manifests as highly saturated noise and edge artifacts.

Version 2.5 uses a cost function that considers a noise parameter in addition to the mean color difference in order to locate a more robust transformation matrix. The formula is shown in Equation 1 and described in the referenced papers [10-11].

$$N = \sqrt{\Delta L^*_{N^2} + \Delta a^*_{N^2} + \Delta b^*_{N^2}} \quad (1)$$

Where:

$$A = \frac{Y^{-2/3}}{Y_n^{2/3}} = \frac{18.4^{-2/3}}{100^{2/3}}$$

$$\Delta L^*_{N^2} = \left(\frac{116A}{3}\right)(m_{Y,1}^2 + m_{Y,2}^2 + \dots + m_{Y,6}^2)$$

$$\Delta a^*_{N^2} = \left(\frac{500A}{3}\right)\left((m_{X,1} - m_{Y,1})^2 + (m_{X,2} - m_{Y,2})^2 + \dots + (m_{X,6} - m_{Y,6})^2\right)$$

$$\Delta b^*_{N^2} = \left(\frac{200A}{3}\right)\left((m_{Y,1} - m_{Z,1})^2 + (m_{Y,2} - m_{Z,2})^2 + \dots + (m_{Y,6} - m_{Z,6})^2\right)$$

- N represents the noise parameter.
- X , Y , and Z represent tristimulus values using the 1931 standard observer.
- Y_n indicates the luminance of the white point, defined as 100.
- $m_{X,i}$ indicates the coefficient of the 3 x 6 color transformation matrix that describes the contribution of channel 1 to the X tristimulus value. Similarly, $m_{Z,3}$ describes the contribution of channel 3 to the Z tristimulus value, and so on. Each row must be rescaled so that the sum of the coefficients is equal to 1.
- For middle gray, $Y=18.4$, which is selected for this optimization.

Chunking images

During several steps in pre-processing, the images are chunked into smaller pieces to increase efficiency. The chunks are processed in parallel (simultaneously) across the user's CPU. This decreases the likelihood of running out of memory and increases the pre-processing speed by 1.5 times. This will have the largest impact when used with slower computers, larger images, or large batches of images.

New Features

Embedding an iccMAX profile in the output images

In addition to the color-managed TIFF, Beyond RGB 2.5 outputs a 6-channel spectral image that contains an iccMAX profile. One of the advantages of iccMAX is that it has a very flexible format, allowing for the embedding of diverse profiles in images with any number of channels. In this case, the spectral transformation matrix is stored, which can be used to estimate the spectral reflectance at each pixel. It should be noted that iccMAX profiles are stored as a tag within ICCv4 profiles. As such, opening the 6-channel image with legacy software that does not support iccMAX will result in an inaccurate color appearance. For visual accuracy, the 3-channel image should be used, which is rendered in the ProPhoto space. Further details regarding iccMAX can be found on the [ICC website](#) [12].

Support for the OpenQualia Label Standard

Beyond RGB 2.5 encourages best practice by including support for the OpenQualia Label Standard. This is a proposed standard that facilitates and simplifies the use of target-specific measurements. These measurements can be uploaded to the OpenQualia server and accessed via a QR code that travels with the target. Targets of the same type and manufacturer vary in spectral reflectance, so using

generic target measurements can significantly reduce color accuracy [13]. More details about the OpenQualia Label Standard are available on the [website](#) [14].

Beyond RGB includes generic measurements for common color targets for users without access to custom target measurements. There is also support for the user to upload custom data, which must follow a strict, predefined template. However, the software now supports data uploaded in the OpenQualia format, which can be downloaded directly from the server. Users can pull this data directly from a QR code in the image rather than managing separate data files which can be easily lost, corrupted, or mixed up.

Enabling target rotation

For the software to use the color targets for profiling, the user must manually indicate the locations of the color target patches. This is done by overlaying a grid on the image so the software can extract pixels from selected regions. Previously, the orientation of the grid was fixed. If the target was rotated in the scene, custom data files needed to be created by swapping the rows and columns. Similarly, if the target was slightly tilted, positioning the grid to avoid edge pixels could be difficult. Version 2.5 includes a rotation feature that addresses these issues. Figure 6 provides an example of images that would require use of the target rotation feature.

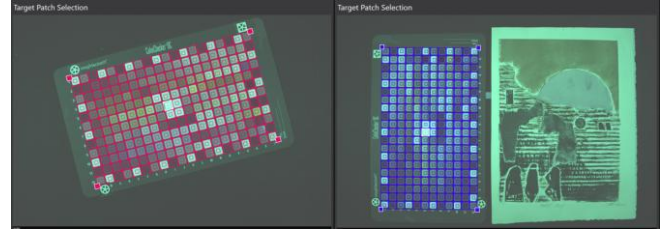


Figure 6. Example of images containing targets that would require rotation, including an exaggerated tilt on the left, and a 90 degree rotation on the right.

Documenting registration matches

During pre-processing, the two RGB image sets are combined and registered using a feature selection algorithm. Beyond RGB includes a record of the features used for registration in the supporting documentation. This includes a TIFF showing a visualization of the matched points, as shown in Figure 7. Users can quickly examine the match points to locate the features used during registration.

This output may be used to help troubleshoot issues with registering the images. For example, if a set of images frequently shows channel misalignment artifacts, the user may assess which features are causing the mismatch and either remove problematic objects from the scene or include objects such as registration targets to address the issue.

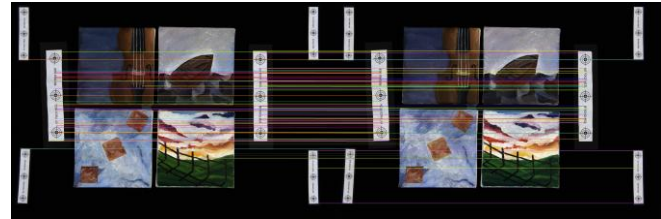


Figure 7. Beyond RGB output showing location of matched registration features between one pair of images.

Improved Usability

Minor improvements have also been made to improve the usability of the software, which are listed below:

- All three major operating platforms (Mac, Windows, and Linux) are supported, and more advanced downloads can be found on the [Beyond RGB website](#) [5].
- Error messages are now displayed with plain text descriptions along with recommended solutions. For users who wish to examine the source code, stack traces are also provided.
- The user interface elements were unified across the application, ensuring that the appearance and location of controls are more intuitive.
- Stability was significantly improved, allowing the user to easily navigate both forwards and backwards between steps.
- Locations of custom target reflectance data are remembered within a session, eliminating the need to manually select the path each time a new set of images is processed.
- Beyond RGB files are output using an identifier to indicate that a set of images and files are grouped together. Users can now select a custom identifier (e.g., time and date) rather than the default numeric string. This is intended to help Beyond RGB output files conform more easily to an existing workflow.
- All known major bugs from previous versions of Beyond RGB have been resolved.

Upgraded Visualizations

Improvements were also made to the visualizations within Beyond RGB. The software includes several visualizations of the profiling accuracy. These plots are discussed in detail in references [7-9]. Here, only the updated visualizations are discussed.

The performance summary page now includes an at-a-glance summary of the mean and 90th percentile ΔE_{2000} error for both the calibration and verification targets. The user can quickly check for signs of overfitting by comparing these values. If the color differences for the calibration target are much smaller than for the verification target, this may indicate overfitting.

The page also contains a color difference heatmap showing the ΔE_{2000} error for each patch in the calibration target, shown in Figure 8. A legend has been added to show the scale of the differences.



Figure 8. Screenshot of the color difference heatmap in Beyond RGB 2.5. Each square represents one patch in the calibration target.

An interactive plot showing spectral reflectance error for each patch is now included on the performance summary page, as shown in Figure 9. The user can compare the estimated and reference reflectance values by hovering over the spectra.

Beyond RGB provides CIELab plots, including a^*b^* and L^*C^* plots to show the location and direction of estimation errors in color space. These plots now have axis controls that allow precise positioning and rescaling. Additionally, the a^* and b^* axes have been fixed to be of equal scale. This is important because CIELab is approximately perceptually uniform, meaning that an equal distance in any direction corresponds to an approximately equal difference in perceived color. Figure 10 shows a screenshot of the a^*b^* plot in Beyond RGB 2.5.

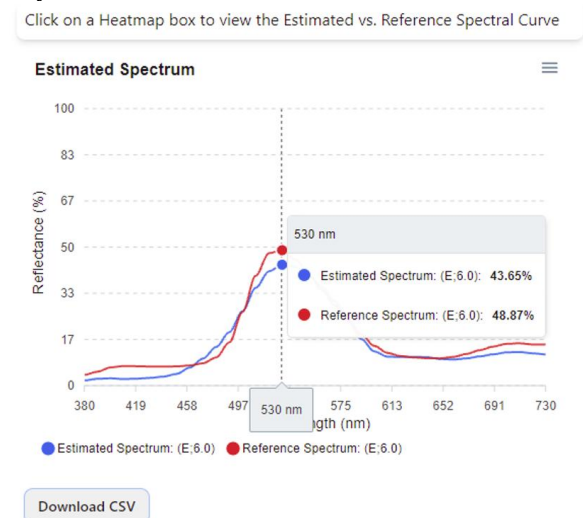


Figure 9. Screenshot of the interactive report on spectral estimation error from Beyond RGB 2.5. Users can select a patch on the heatmap to compare the estimated and measured reflectance. Hovering over the plot provides a numerical summary at different wavelengths.

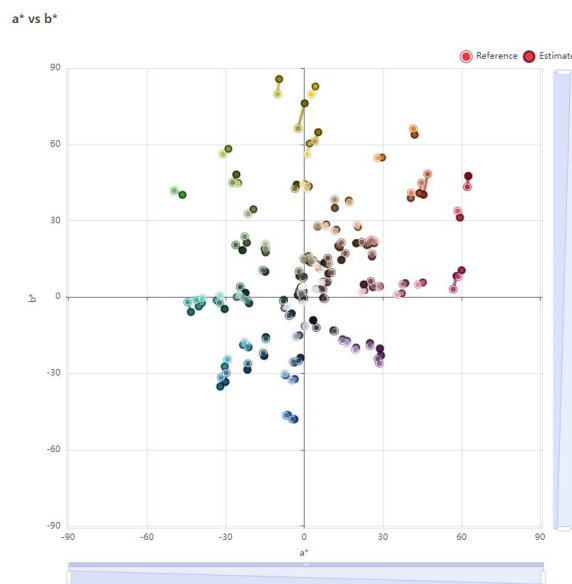


Figure 10. Screenshot of the a^*b^* plot in Beyond RGB 2.5. Note the square grid indicating equal distances in the a^*b^* dimensions. The blue bars on the side are the axis controls.

Limitations and Future Work

The Beyond RGB software is not suitable for all applications. Rather, it is one tool to add to a cultural heritage digitization workflow, which is especially useful for improving color accuracy and low-precision estimation of spectral reflectance.

In particular, the software only accepts images captured with the dual-RGB technique and is limited to the visible spectrum by the native RGB camera sensitivity. Image sets without corresponding flat field, dark current, or color target images cannot be processed.

While the software will process any image set that meets the above criteria, the quality of the final images is highly dependent on the conditions and setup that were used. Using conditions that are poorly matched can result in images with very low image quality, and, in some unusual cases, lower color accuracy than 3-channel image calibrated under a standard white light.

There are several improvements that could be made to the software in the future, including:

- Providing an option for TIFF, JPEG2000, or PDF/A output images in accordance with the FADGI guidelines
- Allowing the user to select color spaces between ProPhoto, Adobe RGB (1998), and ECIRGB_v2 in accordance with the FADGI guidelines
- Accepting DNG input images formatted according to the upcoming standard (ISO 12234-4:2026)
- Giving the user more control over output files to better fit into established workflows

Most of the features incorporated in Beyond RGB since its first release were recommended by members of the cultural heritage community. We always welcome further suggestions and feedback.

Conclusion

Beyond RGB is a free, open-source image processing software designed to lower the barrier to entry for spectral imaging in cultural heritage contexts. It takes input from two sets of spectrally distinct RGB image pairs and color target reference data to produce color-managed images and supporting documentation.

Major improvements have been made to version 2.5 of this software. Changes have been made to the processing pipeline to reduce noise and increase efficiency. New features have been included that alter how the user can interact with the software interface and output files, including embedding iccMAX profiles and support for the OpenQualia Label Standard. Finally, an assortment of updates has been made to increase the usability of the software in a cultural heritage context and improve the visualizations for easier interpretation and handling.

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Author Biography

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Jakob J. A. Langtry is a fifth-year Software Engineering student at RIT, graduating May 2026. He is a member of the Society of Software Engineers and a contributor to Beyond RGB, an open-source spectral image processing application. Jakob's personal development work spans full-stack development, systems programming, and cross-platform desktop applications.

Susan Farnand is the Graduate Program Director of, and an Associate Professor in, the Program of Color Science at RIT. Her research interests center around human color vision and perception including individual color vision differences, visual attention, color imaging, image quality metrics, 3D printing, and archiving. She holds a BS in Engineering from Cornell University, an MS in Imaging Science, and a PhD in Color Science from RIT. Dr. Farnand is a past IS&T President.