METACOW: A Public-Domain, High-Resolution, Fully-Digital, Noise-Free, Metameric, Extended-Dynamic-Range, Spectral Test Target for Imaging System Analysis and Simulation

Mark D. Fairchild and Garrett M. Johnson
Munsell Color Science Laboratory, Center for Imaging Science
Rochester Institute of Technology, Rochester New York, USA

Abstract

Standard, easily accessible, test targets have long served the field of color imaging as a foundation for comparison of the performance of various imaging systems and algorithms and the open and meaningful exchange of research results. This paper details the creation and application of a new digital color test target useful for research and development of color imaging systems. The target has several advantages over previous types of targets that include spatial resolution, dynamic range, spectral resolution, metameric properties, lack of noise, and continuous tonal variations. All these features can be important for visual assessment, computational analysis, and colorimetric evaluation. This target, known as METACOW, is freely available to all performing research in color imaging.

Introduction and Objectives

Test targets of various sorts have been tremendously helpful in color imaging research and development. Perhaps the most widely used and recognized instantiation is the GretagMacbeth ColorChecker color rendition chart originally designed by McCamy *et al.*[1] approximately 30 years ago. The ColorChecker was designed with an array of 24 color patches that could be easily evaluated visually and instrumentally. The design was such that the spectral reflectance characteristics of the chart, not just the colors, were created to simulate objects of special interest such as blue flowers (notoriously difficult to reproduce with photographic color film), skin tones, and a nonselective gray scale. The ColorChecker has been so widely used, and was so effectively designed, that its 24 color patches can often be considered as memory colors to scientists and engineers in color imaging.

More recent evolution of digital photographic systems have prompted the evolution of the ColorChecker to a new second form embodied as the GretagMacbeth ColorChecker DC color reference chart.[2] The ColorChecker DC serves similar purposes, but with an order of magnitude more patches (237 instead of 24) it was designed with some of the open-systems properties of digital color imaging in mind. It includes replicate gray scales around the chart to evaluate the spatial uniformity of color balance and tone reproduction. The large number of patches and extended gamut facilitate use of the ColorChecker DC in construction of ICC profiles for scanner or camera characterization. And while reproduction of the ColorChecker DC can be evaluated both visually and instrumentally, visual evaluation is far more difficult with such a large number of color patches. It is safe to assume that the 237 patches of the ColorChecker DC will never become widely recognized memory colors and that the usefulness of the target in psychophysical experiments is somewhat limited.

Similar applications are served by test targets such as the well-known ANSI IT8 targets[3,4] that consist of large numbers of well-characterized color patches that can be used for scanner characterization and related applications. Again, such targets are of limited practical use in psychophysical evaluation of imaging systems due the large number of patches although some versions have a small area of pictorial content more amenable to human judgement.

For visual evaluation of imaging systems or imaging algorithms, standard (actual or de facto) pictorial images are often used by various investigators to allow comparison of research results and combination of data from various studies. Well-known examples include the SCID, standard color image data, and SHIPP, standard high precision picture data, images that are available in digital form in various color representations.[5-7]

Previous examples provide targets that well represent two categories of need. The first are well defined spectrally and instrumentally but often with too many patches for easy visual evaluation. The second are standard digital images that are well defined colorimetrically and appropriate for visual evaluation, but difficult to assess instrumentally. They are also potentially impacted by the original image capture technology. The objective of the test target described in this paper is two bridge the gap between those two categories and produce an image that can be used in research and development that is both well specified spectrally and contains continuously shaded areas that are useful for perceptual judgements. This image is not intended to replace both of the previous categories, but rather to supplement them with a new type of test image with significant practical utility. Additional objectives in the development of this target include eliminating noise in the target itself, including metameric reflectance pairs, and being of sufficient spatial and photometric resolution to be applicable to the evaluation of essentially any imaging technology. The addition of metameric reflectance pairs alone is a significant advance in practical utility over previous color charts.

Rendering System

To meet the objective of creating a noise-free test target, one must rely on computer image synthesis techniques since any image capture or measurement system will have inherent noise characteristics. The limiting factors in the image specification then become spectral resolution, spatial resolution and photometric dynamic range (expressed in terms of quantization). These issues have been previously addressed through en extension of the OpenGL image rendering API to enable rendering of spectral images.[8,9] In particular, the need for such extensions in order to accurately synthesize certain color phenomena such as illuminant metamerism, observer metamerism, and fluorescence have been described, verified, and implemented.[9]

The Johnson and Fairchild[8,9] extensions to OpenGL have been made publicly available and they formed the basis for the rendering system used to generate the new test target.[10] The test target is made up of 24 copies of a three-dimensional rendered model of a cow with base reflectance characteristics similar to those of a GretagMacbeth ColorChecker on one half of each cow and a metameric match to those reflectances (CIE Illuminant D65, 1931 Standard Colorimetric Observer) on the other half of each cow. The 3D cow model is in the public domain and the fully rendered image is now also being placed in the public domain. Rendering was accomplished on a hardware-accelerated system using the spectral OpenGL extensions. Due to hardware limitations, each wavelength and cow element (of the 24 total cows) was rendered individually and the final image was stitched together both spatially and spectrally to form the final target. Rendering was completed using an SGI Onyx2 InfiniteReality2 graphics supercometer with the time required to render each cow at a single wavelength (1000x1000 pixels per cow) equal to approximately 0.01389 second. The rendered images are then stored as 16-bit integers for each pixel and wavelength. The glossy cows are rendered using a single directional light source, a Phong reflection model, and Gouraud shading. This is a local illumination rendering technique thus no inter-reflections between the cows are rendered in the test target.

Test Target Specification

As indicated in the paper title, many adjectives can be used to describe the objectives for this test target and its ultimate embodiment. The METACOW (short for metameric and cow) test target is public domain, high resolution, fully digital, noise free, metameric, extended dynamic range, and spectral. Each of these features is described in more detail in the following paragraphs.

Public Domain

The METACOW test target is not a commercial product and has absolutely no restrictions in its use, publication, or distribution. The authors only request that users reference the source of the image when its use is reported. There is no cost for the image data itself although the authors will charge a nominal fee to those directly requesting copies to cover production, materials, and shipping fees for the DVD-ROM.

High Resolution

Each cow element of the METACOW image was rendered at a resolution of 1000 by 1000 pixels to fall within the resolution limits of the hardware frame buffer (up to 2K by 2K possible) and keep the total image size small enough to fit on a single DVD-ROM without compression. The entire image is made up of an array of 6 by 4 cows (24 cows representative of the 24 color patches on the original GretagMacbeth ColorChecker). Thus the full METACOW image has a total spatial resolution of 6000 pixels wide by 4000 pixels high (plus a small label area of 200 pixels along the bottom). This resolution should be adequate for display on various image media and/or simulation of such media while preserving spatial dimensions adequate for psychophysical evaluation. For example, METACOW rendered at 300 pixels/inch would result in a 20” x 13.33” image and rendered at 1200 pixels/inch would be a 5” x 3.33” image.

Fully Digital

Since the image is synthetic, no part of its content ever existed in an analog form. Therefore there are no additional artifacts of sampling (spatial or spectral) or quantization. Due to storage constraints (distribution on a single DVD-ROM), the image was rendered in a 16-bit form linear in reflectance (or luminance). While a floating-point representation would have been preferable, it would have required other compromises not deemed appropriate at this time. The image is also subject to design decisions on spectral and spatial sampling. It is hoped that both dimensions are sampled adequately for most, if not all, potential applications.

Noise Free

Since the image is created in a digital environment and directly stored with no additional manipulation, there is no opportunity for the introduction of noise artifacts. This is also a property of the rendering technique utilized. It is worth noting that some image synthesis techniques deliberately introduce noise to simulate various phenomena, mask aliasing, or enhance sharpness. The InfiniteReality2 graphics hardware used to render this image incorporates hardware 8x8 sample anti-aliasing to avoid artifacts in the final image (essentially, within a polygon, 64 pixels are rendered for each final pixel in the image and then averaged). The noise-free nature of the METACOW image is a significant advantage over scanned standard test images for applications in which imaging systems are being simulated. This allows the simulation and evaluation of various noise-inducing components of the imaging system being studied.

Metameric

Illuminant and observer (or instrument) metamerism are critical phenomena in color imaging that are often neglected in test images. Perhaps the single most important contribution of the METACOW test target is the inclusion of metameric pairs for each of the 24 rendered colors. This was accomplished by defining each cow object in two halves (front and rear) and assigning different reflectance properties to each half prior to rendering. One half of each cow is assigned the spectral reflectance properties measured from a GretagMacbeth ColorChecker while the other half is a metameric match to that reflectance for CIE Illuminant D65 and the 1931 CIE Standard Colorimetric Observer (2°). The metameric reflectances were defined by adding a randomly generated linear combination of the metameric black spectra published by Wyszecki and Stiles[11] to each of the ColorChecker spectral reflectances. The linear combinatiosn were generated with the constraints of matching for Ill. D65 and the 1931 observer while maximizing the color difference for Ill. A and the same observer. A different metameric black was used for each cow. Having metameric pairs facilitates evaluation of illuminant and observer metamerism, both visually and instrumentally, in systems simulations. This can be critical in the design and optimization of camera or scanner spectral responsivities.

Extended Dynamic Range

There is certainly significant recent research interest in high-dynamic-range (HDR) imaging. Unfortunately, the METACOW image cannot be considered an HDR image due to both its quantization to 16-bits linear and the nature of the rendered objects. The 16-bits are encoding using the default OpenGL process whereby a perfect reflecting diffuser, viewed at the normal with normal illumination will produce the maximum encoded digital value. More luminous specular highlights, though somewhat rare, are clipped. However the 16-bit quantization, combined with the relatively fine spectral sampling certainly provides for extended dynamic range information compared to most imaging systems. This range should be adequate for the simulation of most imaging systems and is certainly adequate for the simulation of display systems. The choice was made to retain linear in luminance coding to facilitate proper spectroradiometric manipulation of the image for changes in illumination, etc. Only in extreme situations, should this quantization become an impediment to the use of this image and it should never be a problem for psychophysical evaluations of the full image.

Spectral

Lastly, the full METACOW image is a spectral image as suggested by the inclusion of metameric reflectance curves. The image is encoded with a virtual illumination of an equal energy illuminant (sometimes referred to as illuminant E) and thus each pixel can be treated as if it is a reflectance function allowing the introduction of other illuminants via simple multiplication. Of course this does not re-render the image under the new illumination, but that is not an issue since only local illumination was used in rendering. Therefore the end result is the same as if the new illuminant was actually used in the rendering process. The spectral sampling of the METACOW image is 5nm increments in a wavelength range from 380nm to 760nm. This should be adequate to allow simulation of various spectral responsivities in traditional metemeric (*e.g.*, RGB) imaging systems, multi-channel imaging systems, and spectral imaging systems.

The above described features are illustrated in pictorial examples of the properties and applications of the METACOW test target in the next section. They all serve to produce an image with data appropriate for various imaging systems tests and simulations while retaining an appearance (limited number of colors and smooth shading of a recognizable object) that can readily be used in psychophysical experiments with high observer precision.

Example Images and Discussion

The full METACOW spectral image can be rendered to display in an infinite variety of ways. The following examples were designed to illustrate the appearance and features of the image.

Figure 1 shows the full METACOW image as observed by the CIE 1931 Standard Colorimetric Observer under an equal-energy illuminant and then rendered to a typical sRGB computer monitor to create an RGB image. This image is essentially a visual representation of the reflectance characteristics of METACOW.

Figure 2 illustrates illuminant metamerism. The METACOW test target was virtually illuminated by various illuminants and then viewed with the CIE 1931 Standard Colorimetric Observer. The image colorimetric data were then converted to display RGB for final viewing after a CIECAM02 incomplete chromatic adaptation transformation (D=0.7) to compensate for white-point changes.

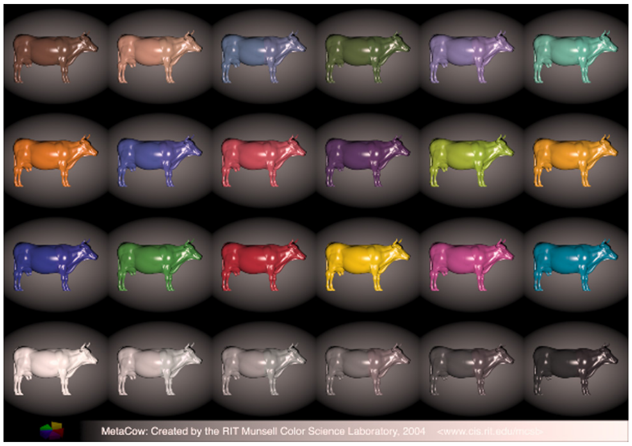

Figure 1. An RGB representation of the visual appearance of the METACOW reflectance image (equal energy illumination).

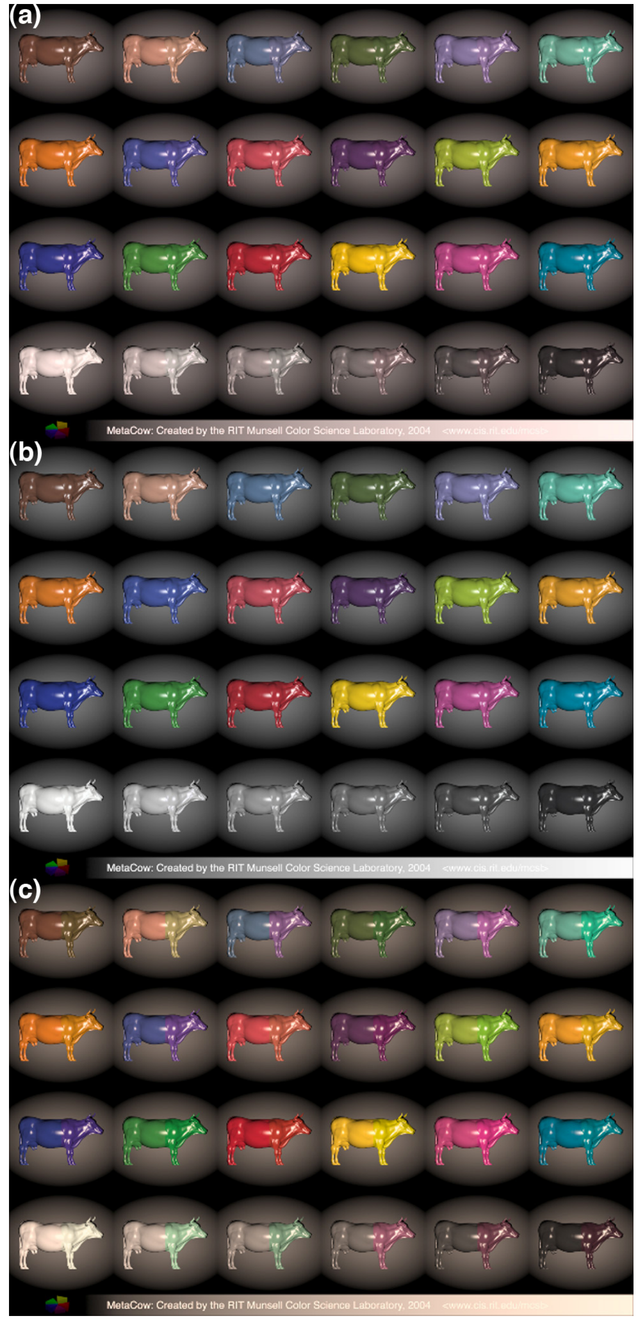

Figure 2. METACOW image rendered under (a) Equal-energy Illuminant, (b) CIE Illuminant D65, and (c) CIE Illuminant A. All viewed by the CIE 1931 Standard Colorimetric Observer (2°).

Figure 3 is an example of the METACOW image used to evaluate observer metamerism. In this case one of the observers is a typical digital camera and another is photographic film. It is clear that metameric matches for an average human observer are no longer matches for these particular simulated imaging sytems. Camera and film RGB values were rendered directly (not a full simulation of the systems, just their metameric properties) with only simple white-point compensation, CIE tristimulus values were first converted to display RGB.

Figure 4 shows how the smooth shading and extended dynamic range in the METACOW test target can be advantageous for psychophysical evaluations. The examples in Fig. 4 are non-adapted (thus not white balanced) illuminant A renderings mapped to display RGB using three different tone reproduction techniques. The first two images illustrate two different image-wide gamma corrections and the third image illustrates a spatially-varying tone-reproduction operator based on the iCAM image appearance model.

Figure 5 illustrates the high spatial resolution and noise free nature of the METACOW target. This image segment is a zoomed portion of the full image rendered on the printed page at 100 pixels per inch.

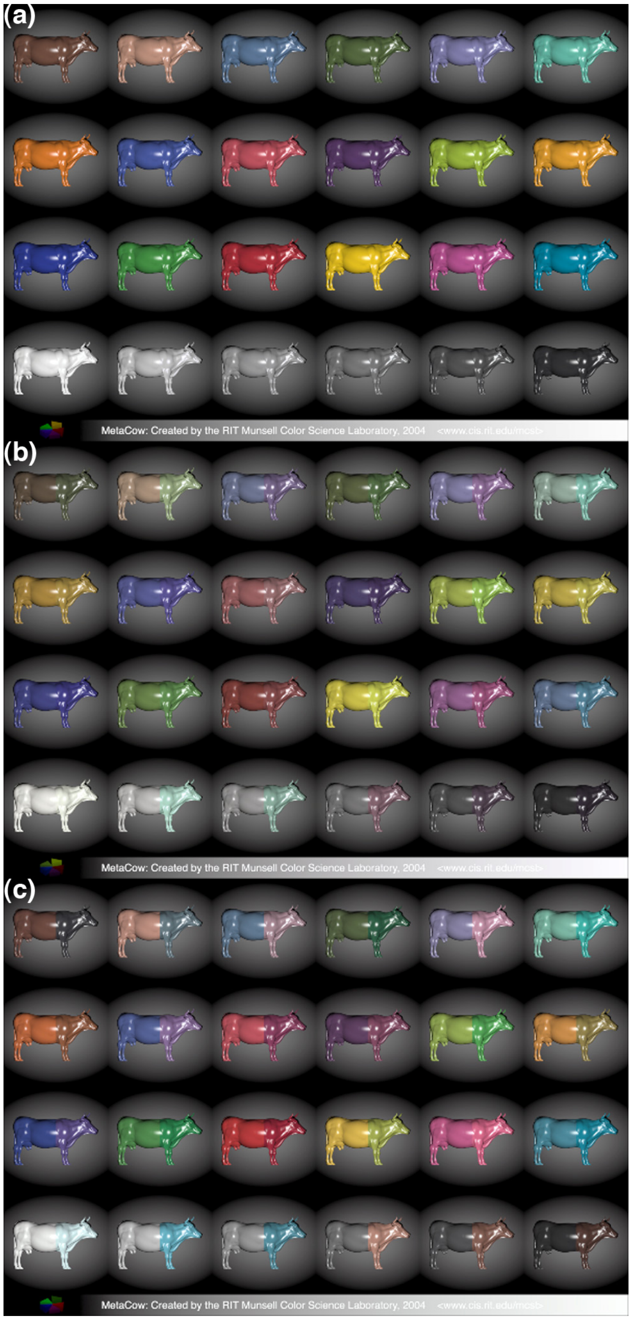

Figure 3. METACOW image rendered under CIE Illuminant D65 and viewed by (a) the CIE 1931 Standard Colorimetric Observer, (b) a typical photographic film, and (c) a three-chip digital camera.

Figure 4. METACOW image rendered with varying tone-reproduction properties and non-adapted illuminant A lighting. (a) Linear in luminance. (b) Gamma correction for a gamma = 1.8 display. (c) Spatially-varying tone reproduction based on iCAM.

Figure 5. Zoomed portion of the METACOW image rendered at 100 pixels per inch on the printed page to illustrate the level of detail available in the original image data.

The examples illustrated above serve to suggest the many potential applications for the METACOW test target. These applications include:

Imaging Systems Analysis & Simulation
- Color Accuracy
- Noise
- Resolution
- Quantization
- *Etc.*

Psychophysical Evaluation

Of particular note are the metameric reflectance properties of the test target allowing critical instrumental and visual evaluation of color reproduction system parameters such as spectral responsivity, tone mapping, color balance, de-mosaicing, and compression.

Conclusions and Availability

Recent advances in off-the-shelf technology have allowed the culmination of research over the past decade to a point where a high-resolution, spectral test image can be readily distributed for essentially no cost. While the full METACOW image would still stress the memory configuration of many computer systems if attempts were made to open the entire file at once and perform manipulations on it, it is quite practical to open and manipulate slices of the image (either spectrally or spatially) and sue it in that way. Certainly, advances in computer technology and memory addressability and cost will allow easy manipulation and display of this image in the not-to-distant future.

The METACOW test target has been made freely available and can be shared in its original digital form without restriction. Due to its large size (approximately 3.7GB; 4200x6000 pixels, 77 wavelengths, 16-bits/pixel), it is available from the authors only in the form of a DVD-ROM. The DVD-ROM will be provided for a nominal fee of approximately $25 to cover expenses related to media, production time, and shipping. Further information can be found at <www.cis.rit.edu/mcsl/METACOW>. A low-resolution version (600x420 pixels with full spectral resolution) is available for download (approx. 10MB). The METACOW DVD-ROM includes the full resolution spectral test target, low-resolution target, example images from this paper, and example MATLAB code to open and read the METACOW image file. The authors only request to those using the image for any sort of research or development is that a citation to this paper accompany its use in any published or presented materials.

Those with the METACOW-DVD are free to make additional copies and distribute them freely with appropriate attribution.

Acknowledgements

This research was sponsored by the Eastman Kodak Company and the Munsell Color Science Laboratory. and the authors thank Lawrence Taplin for his assistance in the production of the METACOW DVD-ROM.

References

1. C.S. McCamy, H. Marcus, and J.G. Davidson, A color rendition chart, J. Appl. Phot. Eng. 11, 95-99 (1976).
2. <http://www.gretagmacbeth.com/Source/Gm.asp?part=Products&page=ProductsDisplay&id=6984&code=d&typ=product>
3. ANSI IT8.7/1-1993, Graphic Technology - Color Transmission Target for Input Scanner Calibration.
4. ANSI IT8.7/2-1993, Graphic Technology - Color Reflection Target for Input Scanner Calibration.
5. JIS XYZ/SCID, JIS X 9204:2000, Graphic Technology - Prepress digital data exchange XYZ/sRGB standard colour image data.
6. SHIPP, XYZ-CIELAB-RGB Standard High Precision Picture data, The Institute of Image Electronics Engineers of Japan.
7. K. Sakamoto and H. Urabe, Development of XYZ/sRGB-SCID and color gamut compression, IS&T/SID 7th Color Imaging Conference, Scottsdale, 212-216 (1999).
8. G.M. Johnson and M.D. Fairchild, Computer synthesis of spectroradiometric images for color imaging systems analysis, IS&T/SID 6th Color Imaging Conference, Scottsdale, 150-153 (1998).

9. G.M. Johnson and M.D. Fairchild, Full-spectral color calculations in realistic image synthesis, IEEE Computer Graphics & Applications 19:4, 47-53 (1999).
10. <http://www.cis.rit.edu/mcsl/research/spectral.shtml>
11. G. Wyszecki and W.S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, Wiley, New York, (1982).

Biography

Mark Fairchild is the Xerox Professor of Color Science and Director of the Munsell Color Science Laboratory at the Rochester Institute of Technology. Garrett Johnson is a Research Assistant Professor in the same laboratory.