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Assessment of RGB Encoding for Color Imaging

Úlfar Steingrímsson and Peter Zolliker

Swiss Federal Laboratories for Material Testing and Research (EMPA),
St.Gallen, Switzerland
ulfar.steingrimsson@empa.ch,
WWW home page: www.empa.ch

Abstract. This work presents validation measures for the optimization of RGB color data encoding. Various RGB specifications had been promoted in the past for standard use in imaging, most of them adapted to application or equipment specific requirements. Although some, as sRGB for instance, are already widely used, none of them has been accepted yet as a universal standard. All of them are subject to limitations regarding to the spatial scope of the color space, making it impossible to satisfy any required conditions in general.
At present, a big variety of different RGB specifications for digital imaging might easily lead to color misinterpretations, because the specific RGB specifications are often missing in the image data. If either the locations of the primary colors or the gamma values are mixed up, color deficiencies are unavoidable. Since the acceptance of a global standard could help to eliminate potential confusions, attempts for the promotion of universal RGB specifications are frequently accomplished.
In the present study, the specific requirements of an RGB in respect of the coding range are examined. A concept for quantitative examination of the encodable color space extent considering the visually perceivable resolution is proposed. Different types of parameters are gathered. First, the fraction of all physically feasible surface colors contained in a certain RGB space is accounted. Next, the visibility of the quantization due to the restricted resolution of the RGB coding is measured in terms of ΔE_{76}. Finally, some widely used RGB definitions are analyzed and assessed on the basis of this evaluation scheme.

1 Introduction

RGB is undoubtedly the most popular color encoding form, having its wide acceptance due to the analogy with the human color perception, as well as to picture tubes where color reproduction is achieved by three separate electron beams onto red, green and blue phosphor targets. However, a generally accepted all-purpose color data RGB is not yet at hand. The present work explicitly addresses the question of an optimally qualified RGB being suitable for universal color data encoding.

RGB is often regarded as a colorimetric de facto standard and thus, many important color image data formats such as JPEG and TIFF refer to RGB without providing precise specifications. However, since RGB primaries, white point as well as gamma exponent making up the accurate definition of an RGB might disagree considerably, serious color shifts must be expected if its appropriate specifications are missing. RGB encoding is usually achieved by 8 bits per channel. Depending on the specific settings, any RGB suffers from certain color restrictions in respect of the color range, the discretization, or both.

The problem of RGB confusion might be approached by providing sufficient information about the RGB by including appropriate standard header entries. The Exif format for instance — actually providing an extended JPEG format — suppies this requirement. Exif is already widely being used by many of the latest digital cameras.

On the other hand, a standard RGB image data format with the prospect of worldwide acceptance is another desirable way to affirm color authenticity. In present practice though, image data originating from digital cameras and scanners are based on substantially varying primaries. The same holds true for image reproduction devices such as monitors and printers. Fig.1 shows the locations of the primaries for some important RGB color spaces, pointing out the manyfold variety. A universally approved RGB standard providing a well defined data link between miscellaneous input and output RGB devices would make up an excellent way to inhibit confusions in RGB data interpretation.

Since all of the currently well known RGB standard color spaces suffer from considerable restrictions in respect of the codable color range and the discretization, none of them could make it to the ultimately acknowledged RGB standard yet. Nevertheless, various standardization attempts had already been promoted more or less successfully. At present, mainly sRGB [1] and Adobe98 RGB are essentially predominant in graphic arts, printing and digital camera industry. Since both include serious limitations of the codable saturation range, most of the digital camera manufacturers additionally provide raw RGB images, being heavily device specific and thus baffling the goal of uniformity.

RGB primaries can be optimized in different ways. Finlayson [2] tweaks for hue constancy, which was also the criterion for the development of the oversized ROMM RGB [11]. Kang [4] reports the computational accuracy of various RGB encoding standards by measuring a printed set of color patches. Katajamäki [5] estimates the optimal gamma value for a specific RGB image in respect of a most even distribution of the image colors. Hill [3] exposes the fundamentals for comparative color space estimations based on examinations in visually equispaced color systems such as CIE Lab. On this background, Braun and Spaulding [10] propose volume based metrics for rating different color encoding types, considering up to which degree a color encoding encloses the "real world surface colors". Separatedly, they evaluate the quantization related color space limits by determining the maximum and the average quantization errors depending on the bit resolution. The latter works include metrics which are qualified for assessing various types of color spaces such as YCC, CIE Lab, RGB and e-sRGB. Though the same holds true for the parameters proposed herein after, the specific goal of this work is to rank color spaces of type RGB only, in order to account for the worldwide promotion of a general color data RGB.

Since on the one hand all devices providing input images usually feature their own well adapted RGB specifications, and on the other hand the same holds true for all image reproducing devices, it is assumed that some kind of color conversion and some device specific gamut mapping has to be performed anywhere within the workflow from the input image to the output reproduction. Standard RGB interfaces for image input or output devices — such as sRGB for monitor output — might in fact be convenient. Yet, they imply restrictions of the achievable color range and hence involve undesirable and oblique extra gamut mapping. A RGB particularly optimized for data encoding should thus satisfy in the first place the demand of being large enough for comprising all existing surface colors and secondly, of enabling a better color resolution than the visually perceivable limits. On the other hand since a data RGB is not intended to release any image reproduction workflow from gamut mapping, its primaries don't necessarily need to agree with any output device.

In the following section, metrics for both features — the color volume and the quantization limits in common — are proposed and the ratings for various RGB types compared with each other.

2 Methods

In the best case, a RGB color space being explicitly designed for image data encoding satisfies three main objectives:

1. It is large enough for encoding all real world surface colors (maximal colors) and ideally, for all theoretically existing surface colors [9] (optimal colors).
2. Colors outside the optimal color gamut are out of our scope since they cannot be realized except by self illuminants. They should thus be avoided.
3. The visual color distances between two adjacent color codes — being limited due to employing usually 8 bits per RGB channel — should be minor than the visually perceivable minimal color distance, that is, less than $1\,\Delta E_{76}$ [8] for all color domains. Ideally due to the Shannon sampling theorem, it would be wise to keep them even below $0.5\,\Delta E_{76}$.

For the determination of the maximal colors, a large set of real world color samples had been collected and its convex hull defined in XYZ (see section 3). The real world colors include Pointer [7], Pantone, Munsell and SOCS [13] colors which are converted to the specifically required illuminants by using Bradford color adaptation [6].

Previous estimation metrics [3, 10] are taking consideration of the main objectives 1-3 separatedly. The goal of this work is to propose one single metric which incorporates all of them.

The basic idea for a model for the evaluation of the three main objectives (points 1-3) includes two issues:

1. The color volume as well as the discretization considerations are accomplished in CIE Lab which is assumed to be perceptibly uniform.
2. Each data sample encodes the color scope of a parallelepiped with a side lengths of $\Delta E_{76} = 1$ at most, assuming that the eye is capable to perceive color differences of $\Delta E_{76} > 1$. That means if adjacent color codes are by less than $\Delta E_{76} = 1$ apart from each other, the spanned color volume corresponds to the volume of the parallelepiped. If one or more color distances are larger than 1, they are truncated. Thus, each particular color code may cover the volume of a parallelepiped with maximal side lengths of $1\,\Delta E_{76}$.

The spacings between two adjacent color codes

$$\underline{\Delta_{RGB}} = \begin{pmatrix} R \\ G \\ B \end{pmatrix} - \begin{pmatrix} R + \Delta_r \\ G + \Delta_g \\ B + \Delta_b \end{pmatrix} = \underline{RGB} - \underline{RGB}_{\Delta_{r,g,b}}, \quad \Delta_{r,g,b} \in [0, 1] \tag{1}$$

are converted to CIE Lab resulting in three vectors limited to $1\ \Delta E_{76}$ each, spanning a single color fragment, yielding

$$\underline{\Delta Lab}_r = min\left(\left|\underline{Lab}_{(\underline{RGB})} - \underline{Lab}_{(\underline{RGB}+\Delta_r)}\right|, 1\right), \quad \Delta_r = (1, 0, 0) \tag{2}$$

$$\underline{\Delta Lab}_g = min\left(\left|\underline{Lab}_{(\underline{RGB})} - \underline{Lab}_{(\underline{RGB}+\Delta_g)}\right|, 1\right), \quad \Delta_g = (0, 1, 0) \tag{3}$$

$$\underline{\Delta Lab}_b = min\left(\left|\underline{Lab}_{(\underline{RGB})} - \underline{Lab}_{(\underline{RGB}+\Delta_b)}\right|, 1\right), \quad \Delta_b = (0, 0, 1) \tag{4}$$

The sum of all color fragments being encodable with N bits and additionally being located within the range of the maximal colors V_{ref} yields the codable color volume of a specifi c RGB space

$$V_{Lab} = \sum_{\underline{Lab}_{(\underline{RGB})} \in V_{ref}} det\left[\underline{\Delta Lab}_r, \underline{\Delta Lab}_g, \underline{\Delta Lab}_b\right] \tag{5}$$

A second signifi cant metric is the maximal color distance between two adjacent codes in a color space, being given by

$$d_{Lab} = max\left[\underline{\Delta Lab}_r, \underline{\Delta Lab}_g, \underline{\Delta Lab}_b\right]_{\forall \underline{Lab}_{(\underline{RGB})} \in V_{ref}} \tag{6}$$

3 Verification

According to section 2, determining the codable color volume by summing up the volume fragments provides the advantage of being able to truncate the side lengths of each single encoding fraction to a well defi ned maximum size which corresponds with the visual capabilities.

Without providing this benefi t, the color volume could be calculated much more effi ciently by using convex hull techniques. Since any color space in the CIE Lab system may easily contain concave fragments, a gimmick is required if convex hull techniques are used. According to Grassmann's law the CIE XYZ color space obeys the rules of linearity and additivity. Hence, a color space in XYZ is supposed to be convex provided that additive color mixtures are allowed. The transformation of a convex surface from CIE XYZ into CIE Lab then brings back the concavities, provided that the surface is suffi ciently well sampled.

Based on comparisons with the results of the above convex hull technique, the accuracy of the color volume determination by summing up discrete parallelepipeds according to equations 2-5 — while omitting the constraints to $1\ \Delta E_{76}$ — has been examined. The average of the two unequal calculations disagrees by $<< 1\,\%$ only, making evident that the summing up approach yields results of satisfactory accuracy.

4 Results

The following well known RGB color spaces [2, 4, 12] have been judged according to the metrics of section 2:

Adobe 1998	Generic EBU Monitor	PAL
Adobe Monitor	Generic Monitor	ROMM
Apple	Kodak DC	SMPTE
Bruce Fraser	Kodak Open Interchange	sRGB
Color Match	NEC Multi Sync Monitor	Wide Gamut
ECI	NTSC 1953	

The encodable color volumes have been evaluated by applying equation 5 and the findings have been compared to conventional color space computations. Fig.2 points out the relative difference of conventional volume estimations to those according to equation 5 implicitly considering quantization. The comparatively large ROMM RGB space has been evaluated at variable bit rates. The results make evident that assigning less than 8 bits per RGB channel yields serious deficits in the color encoding capability since the color graduation becomes too coarse. Encoding with 8 bits seems to be just the minimally required resolution. The evaluation is based on the discernible color limit of $\Delta E_{76} = 1$.

The color gaps effected when using 8 bits per channel are evaluated in Fig.3 for all considered RGB definitions. The graph points out the mean values and the variations, as well as the minimal and maximal values of all color distances between two adjacent color encodings. Only those colors within the maximal color space have been considered, since the colors outside this range cannot be reproduced by any image reproduction technique yet and thus they are non-essential. The RGB definitions are sorted by the maximum color distances ranging from 1.2 at the smallest RGB spaces up to more than 2.0 at some large spaces, yielding insufficient resolution in certain color areas.

Two significant metrics — firstly, the relative coverage of all maximal colors and secondly, the mean color distance of every two adjacent color codes — have been chosen to classify RGB specifications regarding to suitability for data encoding. Fig.4 displays the rankings of all RGB types listed at the beginning of this chapter. As outlined in section 2, an optimal RGB encoding would provide both, a high coverage of all maximal colors as well as a preferably high resolution of the color encodings. The second goal agrees with a low mean color distance between adjacent codes. The two intentions however conflict with each other as is manifested by the relatively high correlation rate of $\varrho = 0.79$, signifying fairly contradictive objectives.

In Fig.4, the scope which is favorable for RGB data encoding is outlined with a shaded area. It includes the four RGB specifications *Adobe 1998*, *NTSC 1953*, *ECI*, as well as *Kodak Open Interchange* RGB. Though the two candidates *ROMM* and *Wide Gamut* RGB include large parts of the maximal colors, its mean color distance is too large. RGB candidates such as *sRGB*, *SMPTE*, *Kodak DC* and *PAL* RGB are not optimal in respect of both ratings.

5 Conclusions

A valuation strategy has been proposed to judge RGB specifications in respect of exclusive data encoding. The metrics combine the codable color gamut size with attributes associated with the discretization.

Various common RGB definitions have been examined according to this evaluation scheme. It comes out that in particular four RGB candidates are well qualified for data encoding purpose, namely *Adobe 1998*, *NTSC 1953*, *ECI*, and *Kodak Open Interchange* RGB.

In this work, only existing RGB specifications have been assessed. However by arbitrary variation of RGB primaries and the gamma value, an optimization in terms of color data codability could well be achieved by using the proposed metrics.

References

1. M. Anderson, R. Motta, S. Chandrasekar, and M. Stokes. Proposal for a Standard Default Color Space for the Internet: sRGB. In *Color Science, Systems, and Applications*, volume 4, pages 238–245, Scottsdale, Arizona, 1995. IS&T's 4th Color Imaging Conference.
2. G.D. Finlayson and S. Süsstrunk. Optimization for Hue Constant RGB Sensors. In *Color Science and Engineering Systems*, volume 10, pages 343–348, Scottsdale, Arizona, November 2002. IS&T's 10th Color Imaging Conference.
3. B. Hill, Th. Roger, and F.W. Vorhagen. Comparative Analysis of the Quantization of Color Spaces on the Basis of the CIELAB Color-Difference Formula. *ACM Transactions on Graphics*, 16(2):109–154, April 1997.
4. H.R. Kang. Computational Accuracy of RGB Encoding Standards. volume 16, pages 661–664, Vancouver, Canada, November 2000. IS&T's NIP16: International Conference on Digital Printing Technologies.
5. J. Katajamäki and P. Laihanen. Image Dependent Gamma Selection Based on Color Palette Equalization and a Simple Lightness Model. In *Color Science, Systems, and Applications*, volume 7, pages 301–306, Scottsdale, Arizona, November 1999. IS&T's 7th Color Imaging Conference.
6. K.M. Lam. Metamerism and Colour Constancy. Ph.D. Thesis, 1985. University of Bradford.
7. M.R. Pointer. The Gamut of Real Surface Colours. *Color Research and Application*, 5(3):145–155, Fall 1980.
8. A.R. Robertson. The CIE 1976 Color-Difference Formulae. *Color Research and Application*, 2(1):7–11, Spring 1977.
9. E. Schrödinger. Theorie der Pigmente von grösster Leuchtkraft. *Annalen der Physik*, 4(62):603–622, 1920.
10. K. Spaulding and G. Braun. Method for Evaluating the Color Gamut and Quantization Characteristics of Output-Referred Extended-Gamut Color Encodings. In *Color Science and Engineering Systems*, volume 10, pages 99–105, Scottsdale, Arizona, November 2002. IS&T's 10th Color Imaging Conference.
11. K.E. Spaulding, G.J. Woolfe, and E.J. Giorgianni. Optimized Extended Gamut Color Encoding for Scene-Referred and Output-Referred Image States. *Journal of Imaging Science and Technology*, 45(5):418–426, September 2001.
12. S. Süsstrunk, R. Buckley, and S. Swen. Standard RGB Color Spaces. In *Color Science, Systems, and Applications*, volume 7, pages 127–134, Scottsdale, Arizona, November 1999. IS&T's 7th Color Imaging Conference.

13. J. Tajima, H. Haneishi, N. Ojima, and M. Tsukada. Representative Data Selection for Standard Object Colour Spectra Database (SOCS). In *Color Science and Engineering Systems*, volume 10, pages 155–160, Scottsdale, Arizona, November 2002. IS&T's 10th Color Imaging Conference.

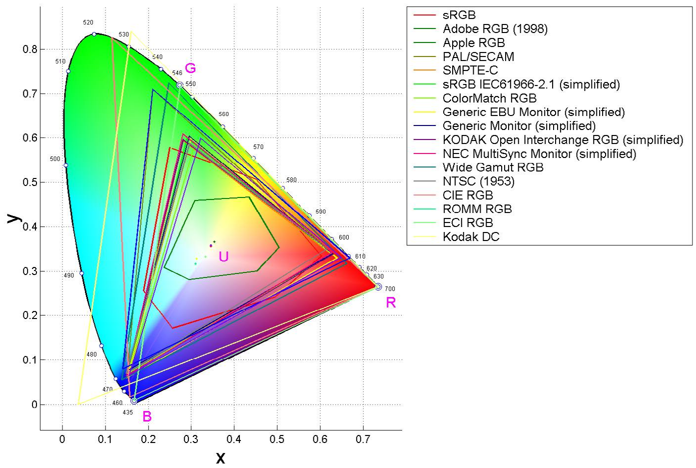

Fig. 1. Common RGB spaces being adopted by digital cameras, scanners, monitors, or merely serving as working color spaces for image analysis and archiving purpose. The figure shows the well known horseshoe shaped xy color space representation.

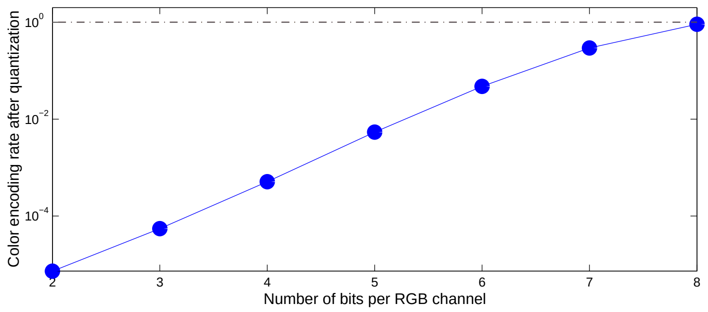

Fig. 2. This figure illustrates the impact of the quantization according to equation 5. The limitation to $1\,\Delta E_{76}$ of the color space fraction recordable with a single code yields substantial color space shortcomings whenever the bit rate of the RGB channels is too low. The figure presents the effective color encoding rates depending on the number of coding bits. The comparatively large ROMM RGB has been evaluated. Even at a bit rate of 7 bits, only about one third of the real world surface colors (maximal colors) are encodable due to the too large color gaps between two adjacent codes. At a bit rate of 8 bits, the sampling rate is reasonably close to the perceptible color resolution.

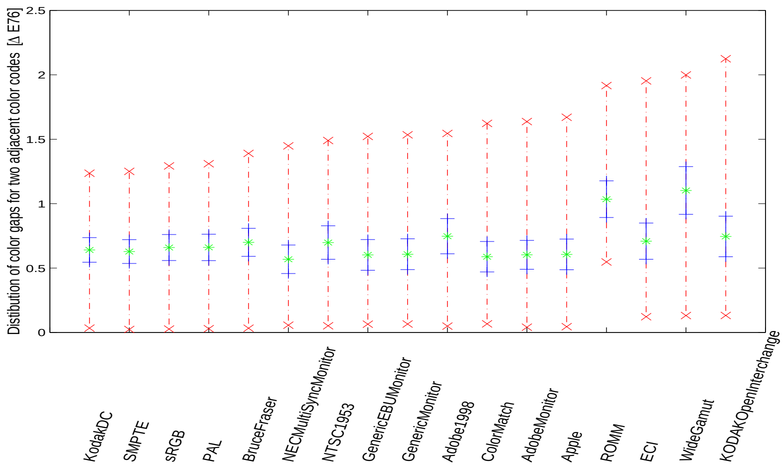

Fig. 3. For the RGB list at the top of section 4, the distribution of the color distances of two adjacent color codes is given by its mean values (displayed by stars), scattering intervals (lines delimited by '+') and minimal / maximal value intervals (delimited by crosses). The RGB characteristics are sorted by the maximal color encoding distances.

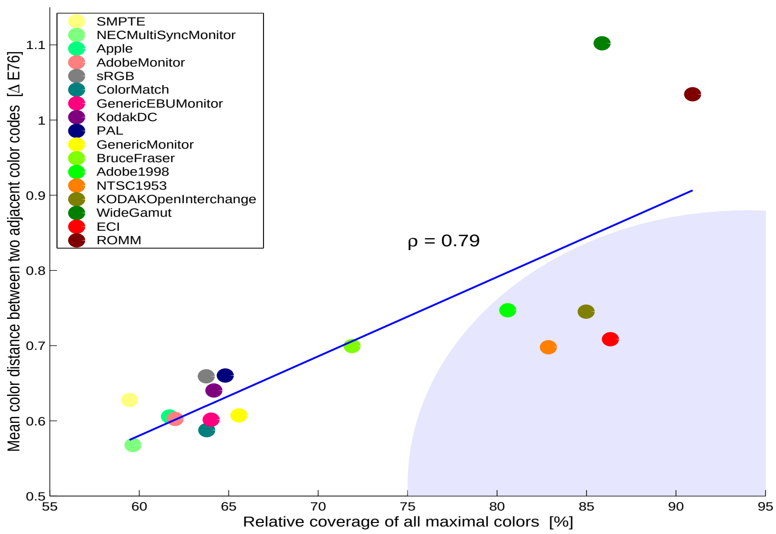

Fig. 4. Evaluation of multiple RGB specifications according to the metrics given in equation 5 and 6. The abscissa shows the percentual portion of all maximal colors being encodable with the respective RGB specifications. The ordinate points out the mean color difference between two adjacent color codes in ΔE_{76}.