LinLogBef File Format for HDR Image

Sergey N. Bezryadin, KWE International Inc, San Francisco, USA

Abstract

A file format suitable for storing a full-color high dynamic range image should allow for keeping image information with an accuracy exceeding color visual threshold. Plane use of a floating-point encoding results in too large files, while the Extended Range format produces more compact files. However, there is still an opportunity for a better result.

This paper suggests file format that not only provides files smaller than Extended Range format and meets the accuracy requirement, but also allows for a trade off between data precision and file size. The format design is based on a coordinate system convenient for brightness, contrast and dynamic range editing which preserves chromatic coordinates.

Introduction

A move from a conventional image, which corresponds to a regular CRT monitor potential, to a full-color high dynamic range image (HDRI) is the issue of today. A file format suitable for storing a HDRI should be able to keep image information with an accuracy exceeding color visual threshold. Plane use of a floating-point encoding (96 bit/pix) produces files which are too large. The Extended Range format (EXR) produces more compact files with about 16 - 20 bit/pix. However, there is still an opportunity for a better result.

This paper suggests a file format that not only can provide files smaller than EXR, while meeting the accuracy requirement, but also allows for a trade off between data precision and file size.

The trade off implementation requires the ability to calculate an error in data description. The error is mostly determined by a quantization error. This paper suggests a quantitative criterion for accuracy of data representation estimation and a color coordinate system convenient for compression and operations with full-color HDRIs.

Quantization Conditions

For digital color encoding, a color space should be subdivided into cells. At quantization, all stimuli associated with a particular cell are replaced by a single representative stimulus which usually corresponds to a center of the cell. If stimuli representing adjacent cells are distinguishable, it may result in aliasing image artifacts. Therefore, the quantization error, which is the difference between two adjacent representative stimuli, should be below visible threshold. On the other hand, the quantization should not be excessive because it affects file size.

Experimental data on color-difference threshold may serve as a base for quantization criterion. The condition for format with lossless or visual lossless compression may be formulated as follows: a quantization cell and centers of all 26 adjacent to it cells must be contained inside one color-matching ellipsoid. In other words, the cell's biggest diagonal should not exceed half of the smallest axis of the associated ellipsoid. For orthonormal fragmentation, a quantization step should be less than $1/(2\sqrt{3})$ of the ellipsoids' smallest axis. It has to be mentioned that stated quantization condition is stronger, than the one described in [1].

Ellipsoids' shape and size depend on metrics used for its calculation. From a practical point of view, the closer color-matching ellipsoids' shapes approximate spheres with the same radius, the better the corresponding metrics, the better it reflects peculiarity of human color perception.

Metrics comparison suggests that Cohen metrics performs better than traditional linear metrics [2] (the summary may be found in Appendix A). Further in this paper all distances are calculated according to Cohen metrics [3].

For any color-matching ellipsoid, as it could be seen from Wyszecki & Fielder data [4], length of its axes exceeds 1% of the length of the corresponding stimulus. Relative quantization error δS may be calculated as

$$\delta S = \|\Delta \boldsymbol{S}\| / \|\boldsymbol{S}\| \tag{1}$$

where $\|\boldsymbol{S}\|$ is length of the representative stimulus, and $\|\Delta \boldsymbol{S}\|$ is length of maximal vector-difference between $\boldsymbol{S}$ and adjacent representative stimuli. If relative quantization error δS is less than 0.5% for all representative stimuli, the quantization meets introduced visual threshold condition. Therefore, for orthonormal fragmentation the quantization step should be less than $0.005\,\|\boldsymbol{S}\| / \sqrt{3}$, or less than 0.3% of stimulus length.

Extended Range Format

The Extended Range format based on a 16-bit half floating-point encoding subdivides a color space into cells with a quantization step less than 0.1% of stimulus corresponding coordinate [5]. This quantization is not only sufficient, it is redundant. And for compression, redundant precision is disadvantage; this is especially noticeable in a region where one of stimulus coordinates changes sign. Tiny stimulus variations, which cannot be registered by human visual system, cause more than a 10-bit change in a pixel coordinate, and this reduces potential of compression.

Chromatic Color Coordinate Systems

Use of chromatic coordinates is beneficial for full-color HDRI file format design. However, they should be used with caution as accuracy might become an issue. For example, one of formulas in Yxy to XYZ transformation that is routinely used in color management

$$Z = Y\,(1 - x - y) / y \tag{2}$$

is very sensitive to quantization step value for small y values.

To illustrate the accuracy problem, a relative change in a stimulus length (1) that corresponds to a 0.001 variation in chromatic coordinates has been calculated in three chromatic color coordinate systems (CCSs) Yxy, Luv and *Bef* (see *Bef* description in Appendix B) for four different stimuli: Blue phosphor of sRGB monitor and monochromatic lights with wave lengths 700nm, 440nm and 405nm. (These particular wavelengths were chosen for illustration purpose because the largest relative quantization error in Yxy and Luv corresponds to stimuli close to monochrome with $\lambda \approx$ 405nm, $\lambda \approx$ 440nm is the max of blue cone sensitivity, and the largest relative error in *Bef* corresponds to stimuli close to monochrome with $\lambda \approx$ 700 nm.) Results are presented in Table 1. The quantization step 0.001 corresponds to a 10-bit chromatic coordinate representation for Yxy and Luv and to an 11-bit chromatic coordinate representation for *Bef* CCS.

Table 1. Relative change in a stimulus length corresponding to a chromatic coordinate quantization step 0.001

	B_{sRGB}	700nm	440nm	405nm
Yxy	0.018	0.005	0.086	0.174
Luv	0.009	0.003	0.030	0.061
Bef	0.002	0.003	0.002	0.002

In case of Yxy CCS, the relative change δS for stimuli with wavelength close to Blue phosphor of sRGB monitor is about 2%, which is greater than the threshold of human's distinguishability. The situation is much worse for stimuli close to monochrome with $\lambda \approx$ 405 nm. For them, the difference between adjacent stimuli is greater than 17%. To maintain quantization error below 0.5%, format based on Yxy CCS needs at least 16 bits for y coordinate. Thus, Yxy is not a good choice for full-color HDR images.

LogLuv32

With Luv CCS, the same discretization provides more uniform results than with Yxy. But for Luv, data in Table 1 corresponds to a 10-bit chromatic coordinate representation, while LogLuv32 format [6] uses 8-bit per chromatic coordinate. Use of an 8-bit encoding increases the relative error. Even inside sRGB gamut, LogLuv32 does not satisfy the formulated earlier condition for a quantization error. With an 8-bit encoding, the relative error δS is more than 2% for Blue phosphor of sRGB monitor and is up to 15% for monochrome with λ close to 405 nm.

A format based on Luv CCS should use 13 bits for chromatic coordinate v, not 8 bits, in order to reduce the quantization error to 0.5% for any stimulus.

On the other hand, stimuli with L coordinate value close to minimum available in this format are described in LogLuv32 with superfluous precision, precision that corresponds neither with accuracy of stimuli coordinates measurement provided by image capturing device, nor with human vision resolution at low luminance. There is no reason to keep data with higher precision than it is guaranteed by the measurement. This superfluity unnecessarily increases file size. Regions with near minimum L value are better described with linear than with logarithmic scale. This description will not affect the accuracy, but will provide smaller image files.

LinLogBef

LinLogBef file format uses LogLuv32 as a prototype and has the following differences:

- It employs Bef CCS;
- It uses a compound linear-logarithmic scale for brightness.

As it could be seen from Table 1, chromatic CCS *Bef* gives distinctly better results than Yxy and Luv. Bef is more uniform than Yxy and Luv, and its overall relative error is smaller. The largest relative quantization error in *Bef* is 0.003. To get the stated 0.5% accuracy, chromatic coordinates in Bef should be taken with only 11 bits, less than it is needed in other two CCSs. A better uniformity makes *Bef* CCS a good base for HDRI format design.

Generally, a logarithmic data representation works better for a HDRI than a half floating-point encoding [5]. However, as it was mentioned above, for an image region with low brightness, it is more appropriate to use a linear scale. A compound linear-log scale for brightness allows reducing file size and is not affecting the overall precision. This paper presents two versions of LinLogBef file format: LinLogBef32 and LinLogBefAdvance.

LinLogBef32

A transition from *Bef* with floating-point encoding to LinLogBef32 with integer encoding may be done in two steps. The first step is scaling

$$\begin{aligned} B_S &= \begin{cases} 256 \cdot B / B_L & if \quad B \le B_L \\ 256 \cdot (1 + \ln(B / B_L)) & if \quad B > B_L \end{cases} \\ e_S &= 512 \cdot e \\ f_S &= 512 \cdot f \end{aligned} \tag{3}$$

where B_L is a brightness at which a linear scale is replaced with logarithmic.

Step two, rounding-up, should be done with the following formulas:

$$\begin{aligned} B_I &= \mathrm{int}(B_S + 0.5) \\ e_I &= \mathrm{int}\left(\begin{cases} e_I - 0.5 & if \quad e_I < 0 \\ e_I + 0.5 & if \quad e_I \ge 0 \end{cases} \right) \\ f_I &= \mathrm{int}\left(\begin{cases} f_I - 0.5 & if \quad f_I < 0 \\ f_I + 0.5 & if \quad f_I \ge 0 \end{cases} \right) \end{aligned} \tag{4}$$

Usually, HDRI is compounded from several pictures with different exposure. If $B_{\min}$ is the minimal non-zero brightness that camera is able to detect at the largest exposure used in the compound image, the following relation may determine the border between linear and logarithmic segments:

$B_L = k\,B_{\min}$

where k=256 for 32-bit Bef.

LinLogBef32 format requires 32 bits per pixel: 12 bit for brightness (B_I) and 10 bits for each chromatic coordinate (e_I and f_I). It guarantees that a quantization error will not exceed 0.7% for $3{\cdot}10^6$ dynamic range. The total supported dynamic range, including the linear interval, is $8{\cdot}10^8$.

Based on a 32-bit data representation, this file format provides the most balanced bit distribution among pixel's coordinates in order to minimize the overall quantization error while supporting the reasonable dynamic range.

However, if file format is not limited to 32 bits per pixel, the supported dynamic range and the precision may be increased. LinLogBefAdvance format described below does not specify the number of bits per pixel coordinate and gives a user an option to chose a preferable data precision.

LinLogBefAdvance

This file format allows for trade off between data precision and image file size by varying the relative precision (1) of the data representation. To get more compact file with the chosen accuracy, image data should be lossless compressed. LinLogBefAdvance can incorporate any lossless compression algorithm.

Currently, the LinLogBefAdvance is the only compressing file format that has precision of data representation as a variable parameter. It gives users an option to trade of between precision and file size and guarantees the chosen precision.

For LinLogBefAdvance, a transition from Bef floating-point encoding to integer encoding should be made with the following formula:

$$\begin{aligned} B_S &= \begin{cases} k\cdot B/B_L & if \quad B \le B_L \\ k\cdot(1+\ln(B/B_L)) & if \quad B > B_L \end{cases} \\ e_S &= C\cdot e \\ f_S &= C\cdot f \end{aligned} \tag{3a}$$

where δ is a chosen relative precision (for example, $\delta = 0.003$)

$k = 1.4\,/\,\delta$

$C = 3\,k$

A rounding-up should be made according to the same formulas that are used for LinLogBef32 (4). The rounded B_I, e_I, f_I coordinates may be temporary stored in integer encoding. The number of bits (16 or 32, for example, depending on the used hardware) used for temporary storing is not important, because further this data will be lossless compressed.

Testing results

As an alternative method to check compliance of Bef32-based fragmentation with experimental data on color visual threshold, the distance between cells centers was measured in MacAdam units of color difference (McA). The max distance between cell center associated with center of Wyszecki & Fielder ellipsoid and centers of 26 adjacent cells is 0.44 McA. The calculation was made for 28 Wyszecki & Fielder ellipsoids [4]. This result guarantees the quantization error of Bef32-based fragmentation is below visible threshold.

The average distance is 0.25 McA. So, the max and the average distance between cell center and centers of 26 adjacent to it cells differ less than two times. So, it may be stated that Bef32-based fragmentation is relatively uniform.

To compare the effectiveness of LinLogBef32 with other compression formats, it was tested on various HDRIs. The result obtained for a commonly referred image memorial.hdr (author Paul Debevec) is about average and may be considered as representative: the size of hdr file is 1309 kB, while the size of bef file is 802 kB at 0.7% data precision (which is better, than accuracy provided by 32 bit Radiance RGBE encoding), and 509 kB at 3% precision (which is better, than accuracy provided by standard sRGB encoding).

Conclusion

Suggested LinLogBefAdvance file format can be used for images with practically unlimited dynamic range and guarantees that the relative error in image data representation would not exceed the pre-chosen value. The only restriction for dynamic range is set by hardware specifications on embedded floating-point data type. In terms of real stimuli description, it means unlimited range.

Appendix A. Metric

According to the criterion of local non-uniformity [2], the smaller $k_{\max}$ and k_{RMS} values are, the better the corresponding metrics.

$$k_{\max} = \max(\,k_i) \tag{A1}$$

$$k_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} k_i^2} \tag{A2}$$

where N - is the total number of Wyszecki & Fielder ellipsoids and $k_i = \mathrm{D}_{\max,i} / \mathrm{D}_{\min,i}$ - is the ratio of the largest and the smallest distances between the center of ellipsoid i and its surface.

Non-uniformity parameters $k_{\max}$ and k_{RMS} calculated for 5 different metrics are presented in Table A1.

Table A1. Coefficients of local non-uniformity

Metric	k_{RMS}	$k_{\max}$
Cone	15.4	38.5
XYZ	11.9	28.6
Lin sRGB	6.4	17.7
Cohen	5.6	12.3
Min_k_{RMS}	4.3	8.5

Cone metrics is based on the assumption, that cone sensitivity Tristimulus values L, M and S are coordinates in an orthonormal system. Therefore, the Parseval's identity may be used for color difference formula

$$\mathrm{D}_{Cone}{}^2 = \Delta \mathrm{L}^2 + \Delta \mathrm{M}^2 + \Delta \mathrm{S}^2 \tag{A3}$$

XYZ metrics presumes basic colorimetric coordinate system XYZ is orthonormal, and color difference should be calculated as follows:

$$\mathrm{D}_{XYZ}{}^2 = \Delta \mathrm{X}^2 + \Delta \mathrm{Y}^2 + \Delta \mathrm{Z}^2 \tag{A4}$$

And in Lin sRGB metrics it is supposed that linearized basic computer coordinate system Lin sRGB is orthonormal, so the following color difference formula should be used:

$$\mathrm{D}_{Lin\ sRGB}{}^2 = \Delta \mathrm{R}_{\mathrm{lin}}{}^2 + \Delta \mathrm{G}_{\mathrm{lin}}{}^2 + \Delta \mathrm{B}_{\mathrm{lin}}{}^2 \tag{A5}$$

As it could be seen from Table A1, local non-uniformity parameters are much smaller for Lin sRGB than for XYZ metrics, which corresponds to Holm, Tastl, and Hordley [7] findings. And while formula (A3) looks like the most natural choice, LMS metrics is far from being optimal.

In Cohen metrics, distance may be calculated with the following formula

$$\mathrm{D}_{Cohen}{}^2 = k \int (P_f(\lambda) - Q_f(\lambda))^2 \,\mathrm{d}\lambda \tag{A6}$$

where $P_f(\lambda)$ and $Q_f(\lambda)$ are stimuli fundamental components, and k is a constant that depends on a unit of measurement.

Although non-uniformity parameters in Cohen metrics are slightly bigger than those of Min_k_{RMS}, metrics corresponding to the absolute min of the k_{RMS} function, I believe that Cohen metrics is a better choice because it has a clear physical meaning.

Appendix B. Color Coordinate Systems *DEF*, *BCH* and *Bef*

The choice of basic CCS influences the efficiency of digital image encoding format and the efficiency of color image editing software. However, CCS that is effective for one editing procedure might be less effective for another. A set of correlated CCSs, *DEF*, *BCH* and *Bef*, [8] responds to the demand. *DEF* is an orthonormal CCS convenient for image resizing. *BCH* is good for brightness, contrast and saturation modification and may be used for HDRI editing. And *Bef*, while it is also good for brightness, contrast and HDRI editing, is convenient for image storing.

Linear CCS DEF2

The primary linear CCS in Colorimetry is CIE XYZ. But it is essentially a non-orthonormal system and this is its big disadvantage. An angle between basis vectors $\boldsymbol{e}_{\mathrm{X}}$ and $\boldsymbol{e}_{\mathrm{Y}}$ is 142° [8].

A linear CCS *DEF2* designed on the base of CIE 1931 data (digit "2" indicates 2° Standard Colorimetric Observer) is orthonormal and may be advised to replace XYZ as a primary CCS.

DEF2 and CIE XYZ 1931 coordinates are related through the following equation:

$$\begin{pmatrix} D \\ E \\ F \end{pmatrix} = \begin{pmatrix} 0.2053 & 0.7125 & 0.4670 \\ 1.8537 & -1.2797 & -0.4429 \\ -0.3655 & 1.0120 & -0.6104 \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad \text{(B1)}$$

DEF2 is designed with the following conditions:

- $D > 0$ and $E = F = 0$ for the standard Day light D_{65}; (B2)
- $E > 0$ and $F = 0$ for monochromatic stimulus with 700 nm wavelength; (B3)
- $F > 0$ for yellow stimulus. (B4)

Having one axis directed along a Day light stimulus significantly simplifies saturation, hue editing and gamut mapping algorithms. *D* axis may be directed along other than D_{65} Day light stimuli (D_{55}, EE etc.).

DEF2 CCS variations with different *D* directions may be useful in chromatic adaptation algorithms and in alteration of a full-color image for a limited gamut of an output device.

Brightness value, if it is defined as a stimulus length

$$B = \sqrt{D^2 + E^2 + F^2} \qquad \text{(B5)}$$

does not depend on conditions (B2), (B3), and (B4). Currently in colorimetry, brightness, by definition, is a psychophysical non-measurable characteristic. But in digital image processing brightness is an essential quantitative parameter, and algorithm developers have to use some measure for it. There is no conventional formula for brightness calculation, and it is a regular situation, when an image-editing tool uses several different measures for it. However, stimuli equally bright by one measure may differ more than 10 times by another. Defining brightness as a stimulus length has a clear physical meaning, well correlates with human perception [8] and is effective in image-editing algorithms [10]. An output of all those algorithms [8-10] will not change if other directions for axes *E* and *F* are chosen, as they do not depend on conditions (B3) and (B4).

Spherical CCS BCH

Some image editing procedures, such as brightness, chroma and hue editing, may be easier described in a spherical than in Cartesian CCS. For these algorithms a spherical CCS *BCH* has been designed.

The situation with chroma and hue in colorimetry is similar to the above-described situation with brightness: usually, they should be used only for non-quantitative references to physiological sensations and perceptions of light. But developers of algorithms for color image editing software are obliged to find a way to describe these stimulus characteristics numerically. In *BCH* CCS the following definitions are used for *B* (Brightness), *C* (Chroma) and *H* (Hue):

B is a norm (length) of a color vector ***S***;

C is an angle between the color vector ***S*** and an axis *D* – a color vector representing day light (for example D65, D55, EE etc.);

H is the angle between the orthogonal projection of the color vector S on the plane orthogonal to the axis *D* and the axis *E*, where the axis *E* is defined as the orthogonal projection of a color vector, corresponding to some fixed stimulus (for example, a monochromatic light with wavelength 700 nm), on the plane orthogonal to the axis *D*.

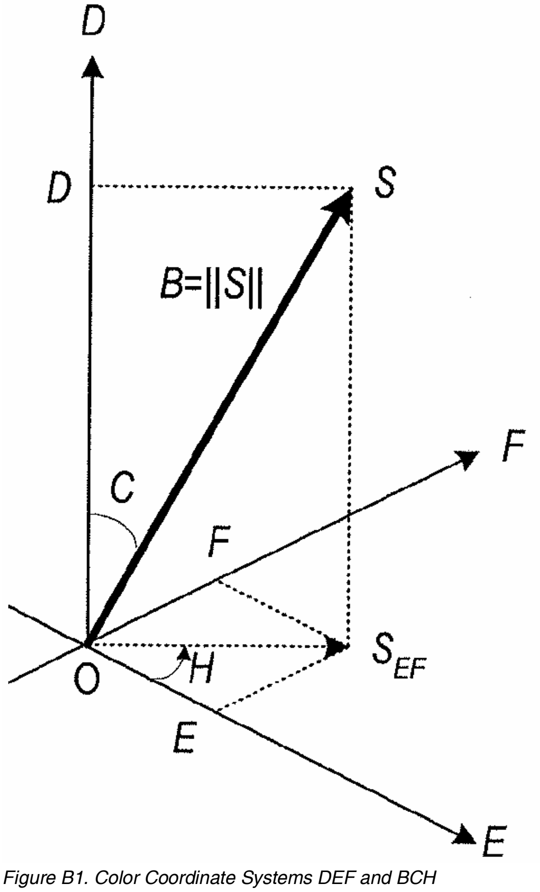

Figure B1. Color Coordinate Systems DEF and BCH

Figure B1 illustrates the relationship between *D*, *E*, and *F* – coordinates of the vector S in the orthogonal CCS *DEF*, and *B*, *C*, and *H* – coordinates of the same vector ***S*** in the spherical CCS *BCH*. Depending on a chosen specification for *D* and *E* definition, there are different variations of *DEF* CCS and, therefore, variations of corresponding *BCH* CCS.

Chromatic CCS Bef

Chromatic coordinates (x,y) and coordinate system xyY are widely used for gamut depicting and for the purpose of illustration of some color image transformations. Introducing similar coordinates in *DEF* is not appropriate because coordinates *E* and *F* might take negative values. Moreover, a vector direction determined by its intersection with a unit sphere has more geometrical sense than coordinates of its intersection with any plane. Therefore, it is reasonable to define chromatic coordinates as follows:

$$e = E / B \qquad \text{(B6)}$$

$$f = F / B \qquad \text{(B7)}$$

where *B* is a length of color vector (B5), and *E* and *F* are the vector's coordinates in *DEF* CCS. So, in chromatic coordinate system Bef, a stimulus has coordinates *B*, *e* and *f* (a color vector length and coordinates of the vector intersection with a unit sphere in *DEF* CCS).

Figure B2 represents a projection of Wyszecki & Fielder ellipsoids and gamut of sRGB monitor in the plane *ef*. It could be seen, that ellipsoids look more uniform in *Bef*, than in Yxy [4].

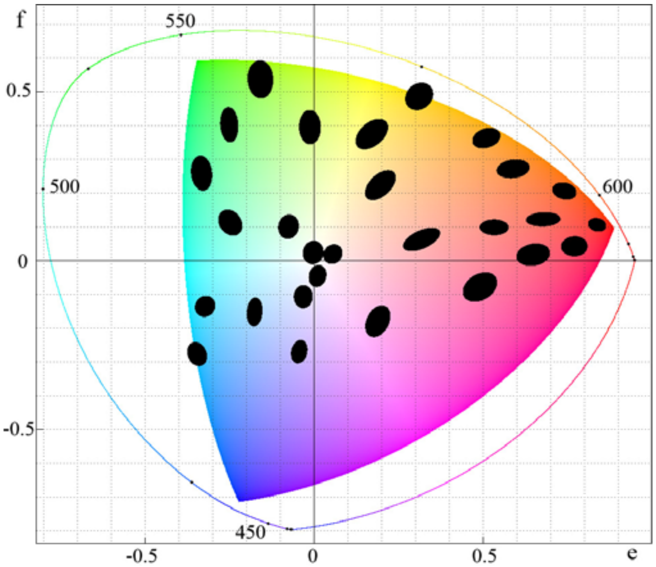

Figure B2. Projection of Wyszecki & Fielder ellipsoids on the plane ef (black). The ellipsoids in the figure are three times their actual size

References

[1] Rafal Mantiuk, Karol Myszkowski, and Hans-Peter Seidel, *Lossy Compression of High Dynamic Range Images and Video,* IS&T/SPIE 18th Electronic Imaging, Proceedings of SPIE Volume 6057: Human Vision and Electronic Imaging XI, (2006).

[2] S. Bezryadin and P. Bourov, *Local Criterion of Quality for Color Color Difference Formula*, IS&T Printing Technology SPb'06, p. 140-144 (2006).

[3] J. Cohen, *Visual Color and Color Mixture: The Fundamental Color Space*, Univ. of Illinois Pr, (2000).

[4] G. Wyszecki & W. Stiles, *Color Science, Concepts and Methods, Quantitative Data and Formulae*, Second Edition, Wiley Inter Science (2000).

[5] E. Reinhard, G. Ward, S. Pattanaik, P. Debevec, *High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting*, Morgan Kaufmann Publishers, San Francisco, 2005.

[6] G.Ward Larson, Overcoming Gamut and Dynamic Range Limitations in Digital Images, IS&T/SID 6th Color Imaging Conference, (1998.)

[7] J. Holm, I. Tastl, and S. Hordley, *Evaluation of DSC (Digital Still Camera) Scene Analysis Error Metrics - Part 1*, IS&T/SID 8th Color Imaging Conference, 279-287(2000).

[8] S. Bezryadin and P. Bourov, *Color Coordinate System for Accurate Color Image Editing Software*, IS&T Printing Technology SPb'06, p. 145–148, (2006).

[9] S. Bezryadin, P. Bourov and D. Ilinikh, *Brightness Calculation in Digital Image Processing*, IS&T Technologies for Digital Fulfillment, p. 10-15, (2007).

[10] S. Bezryadin, *New generation of image editing algorithms*, IS&T/SPIE 19th Electronic Imaging, Proceedings of SPIE Volume 6502: Digital Photography III, (2007).

Author Biography

Sergey Bezryadin received MS in physics from the Moscow State University (1976) and PhD in physics and mathematics from the Moscow Institute of Electronic Technique (1982). Since 2001 he has worked in the KWE International, Inc., San Francisco, USA.