HDR Image Archiving Optimization

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Abstract

The desire to get a better quality and a smaller file size is a usual dilemma in image archiving industry. One of traditional ways to reduce file size is adjusting a color encoding to characteristics of color reproduction device, while improving data precision is usually made by increasing bit capacity.

By using a human-oriented color representation format that does not depend on color reproduction technique it has become possible to achieve better compression ratio at given precision compared to the most popular compression formats for high dynamic range images. The ability to store all visible colors and images with extremely high dynamic range is another benefit brought by the human-oriented approach. The accuracy of image data in this paper is measured in units based on experimental data on color visual threshold, a natural unit tied to human visual system capabilities. With a variable precision parameter it is possible to choose a desired data precision and to make a tradeoff between file size and data precision which is a useful option for digital image archiving.

Introduction

Digital image databases play important role in the modern informational society. Archives, museums, and libraries, professional photographers and magazines are archiving their exhibits in digital form. Large resources of time and money are dedicated to this task and it is important to have an image file format which will ensure the quality of image archiving.

Currently, the most popular image format is JPEG. Nearly half of all professional photographers are still using it for their digital images [1]. However, JPEG's shortcomings are well known and widely criticized, and it is only a matter of time when it is replaced with a more efficient successor.

Growing popularity of high dynamic range (HDR) images and the technological progress in image reproduction devices have set certain requirements for the state-of art archiving format. It is commonly accepted, that such format must support HDR and all visible colors, and there are few well-known formats, such as TIFF, OpenEXR, Radiance HDR (XYZE) and LogLuv, that implement these features [2].

There are also some other aspects which in the author's opinion are essential for the modern archiving the format. First, the format should be device independent. Second, it should provide an option to trade-off between the data precision and the file size. And, finally, it should provide the smallest file size for the chosen precision.

Usually, an image format designer works in the environment of technical decisions accepted by the society on a previous stage of technological evolution. This environment sets certain limits for the designer reducing the options for image archiving algorithm optimization.

This paper discusses the ways to reduce the size of an image file. Retreating from some commonly accepted technological solutions makes it possible to create a format that not only guarantees the pre-chosen image data precision, but also produces the smallest files for full color visual lossless HDR images comparing to other existing HDR formats.

Optimization of HDR Image Archiving

Device Independence

Due to legacy reasons most of visual information today is coded in sRGB format which corresponds to limited capabilities of phosphor-based Cathode Ray Tube (CRT) displays. But with the technological progress of recent years, CRT displays are no longer dominating. Many different display device types that are based on a variety of physical principles of color reproduction are available now. The future display developments promise even greater range of capabilities in color gamut and dynamic range.

However, all well-known HDR formats are tied to a particular type of hardware device what limits their flexibility to keep up with the rapid technological progress. Thus,

- TIFF32 (32 bit per channel) has float type data representation that makes it tied to floating point number representation in PC
- OpenEXR has half float type data representation and this feature ties it to Open GL
- Radiance HDR is tied to backlight LCD HDR type of monitors.

With greater variety of display color reproduction principles it appears unreasonable to tie visual data representation to characteristics of some particular device type. Humans are the recipients of the visual data and therefore the imaging encoding should be tied to the capabilities of human vision. The first format build according to this principle is LogLuv [3] created by Greg Ward.

Variable Precision Parameter

It is well known that sRGB discretization (8 bit per channel) is too coarse and produces image posterization noticeable even on a typical monitor. Simple increasing in the number of bit per channel up to 16 or 32, as it is done in TIFF, leads to too large files. For the visual lossless quality the optimal image archiving format should provide the minimal precision that does not bring in the posterization [4]. The precision parameter should be expressed numerically, and the number should be tied to "just noticeable difference" concept.

Also, it is good to have an option to choose the desired data precision. Different types of consumer may want different data accuracy for their archives. Some would be satisfied with visual lossless quality, other may prefer to get smaller files willing to accept a lower precision, and in some cases it may be important to store original image data with accuracy exceeding visual lossless quality (for example, if extensive contrast or saturation editing is expected in the future).

Therefore, a good archiving format, while guaranteeing visual lossless quality by default setting, should provide the option to increase or decrease the accuracy of storing data. And the format should guarantee it meets the chosen precision. In this case a consumer would know what accuracy he gets for his archive, not just some general "high" or "medium quality" notation.

File Size Minimization

A choice of color coordinate system (CCS) used as a workflow for HDR image compression plays important role in minimizing a file size. While usually linear coordinate systems are very convenient, there are instances, when their effectiveness for color encoding is reduced significantly. This happens when one of coordinates changes sign or one coordinate is much smaller than another. In this case, the use of a linear coordinate system may lead to superfluous data representation. The simplest way to get rid of this effect is to switch to chromatic coordinate system [3,4].

Any image compression technique involves, explicitly or implicitly, color space decomposition, when the space is subdivided into quantization cells, and all color vectors in every cell are replaced with the cell's representative color vector. A method of color space decomposition and the size of quantization cells play important role in file size minimization.

The next common step in reducing file size is lossless decorrelation (for example, with wavelet). The decomposition of the color space should be made in a way that is convenient for the decorrelation. The more uniform is the base color coordinate system, the easier is the decorrelation process.

File size also depends on how small the quantization cells are, so the color space decomposition should be made in accordance to desired precision. The ways to evaluate the accuracy provided by the format are discussed below.

Image Data Precision and its Calculation

Because the critical point in image data accuracy estimation is the visual lossless quality, "just noticeable difference" or Mac Adam unit (McA) is the most natural choice for measuring an error in image data representation. Unfortunately, the regions where experimental data on visual threshold is available and it is possible to use Mac Adam units for stimuli difference measurement make up a very small part of the color space. Therefore, some type of color difference formula has to be used for evaluation of image data accuracy.

There are several more or less popular color difference formulas, but because none of them is entirely in agreement with experimental data, it is useful to have a quantitative parameter which would characterize the degree of correspondence between a formula and human vision. For color difference formula comparison this paper uses coefficient of non-uniformity.

Coefficient of non-uniformity

The coefficient of non-uniformity is based on experimental data on color difference threshold [5] and indicates conformity of a color difference formula with the experimental data. In the ideal case the coefficient is equal to 1. The less a color difference formula conforms with the experimental data, the larger is the corresponding coefficient value. The non-uniformity coefficient is calculated according to the algorithm described below.

First, a small sphere is drawn around the center of each color-matching ellipsoid, so the center of the sphere coincides with the center of the corresponding ellipsoid. All spheres should be identical, with the same radius according to the examined color difference formula. (In some instances, like in case of DE2000, these would not be spheres, but equidistance surfaces.) While any value that is greater than the smallest half-axis and smaller than the largest half-axis of all color-matching ellipsoids is acceptable for the radius, the idea is to get the sphere's size to be about the averaged ellipsoid size. The coefficient of non-uniformity demonstrates good stability in regards to the radius variation. It varies less than 10% for non-linear systems Lab, DE2000 and Δbef.

Then we take about 1,000,000 random points on each of these spheres (or equidistance according to the examined color difference formula surfaces) and calculate their distance from the center in McA. Find the min and max distances among the data for all points and all spheres. The ratio between max and min MacAdam values is the coefficient of non-uniformity for the examined color difference formula. This algorithm is a modified version of the criterion of local non-uniformity [6].

Color difference formula comparison

Table 1 represents coefficient of non-uniformity for some color difference formulas. To calculate a distance in McA, experimental data on Wyszecki & Fielder ellipsoids has been averaged for all experimentalists. In all three cases distance from the center of a color-matching ellipsoid to the surface of the corresponding sphere is equal 1.00 according to the examined color difference formula. The same distance measured in McA is not a constant. The table shows min and max distances in McA for every examined formula.

Table 1. Coefficient of non-uniformity

Color difference formula	minimal distance (McA)	maximal distance (McA)	Coefficient of non-uniformity
Lab (1976)	0.231	1.75	7.59
DE2000	0.79	3.40	4.29
Δbef	0.49	1.69	3.43

As it can be seen from the table, Δbef provides the uniformity most closely correlating with Wyszecki & Fielder data. It is calculated with the following formula

$$\Delta bef = 100\sqrt{(b_1 - b_2)^2 + (e_1 - e_2)^2 + (f_1 - f_2)^2} \quad (1)$$

where

$$b = 0.3\ \ln(B) \quad (2)$$

$$B = \sqrt{D^2 + E^2 + F^2} \quad (3)$$

$$e = E/B \tag{4}$$

$$f = F/B \tag{5}$$

$$\begin{pmatrix} D \\ E \\ F \end{pmatrix} = \begin{pmatrix} 0.2053 & 0.7125 & 0.4670 \\ 1.8537 & -1.2797 & -0.4429 \\ -0.3655 & 1.0120 & -0.6104 \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{6}$$

B is the length of a color vector with coordinates (D, E, F). Color coordinate systems Bef and DEF have been defined in [7].

There is singularity at $B = 0$. In real life there is no light with $B = 0$, because there is no such thing as absolute darkness. However, it is possible in art. The problem may be fixed by replacing zero B values with a small constant, or, what has more physical sense, by modifying formulas (2), (4), (5) as it is shown below:

$$b = 0.3(\ln(B / B_0) + 1) \quad \text{if } B > B_0 \tag{2a}$$

$$b = 0.3\, B / B_0 \quad \text{if } B \le B_0 \tag{2b}$$

$$e = 0 \quad \text{if } B = 0 \tag{4a}$$

$$f = 0 \quad \text{if } B = 0 \tag{5a}$$

Parameter B_0 may be adjusted according to user's preferences. It may be recommended to set B_0 value to the max brightness for which there is still no reduction in human visual system sensitivity due to activation of adaptation mechanism (an automatic gain control), or to the min brightness for which it is still preferable to get the guaranteed data precision.

The complexity of Δbef calculation is comparable to complexity of CIE ΔE_{76}, and significantly less, than it is for DE2000. Aditionally, with Δbef there are no illuminant choice problems when scene has different lighting sources.

Description of bef Format

Design of bef format is made according to the following scheme: quantization, wavelet transformation and Huffman coding. It is a modified version of LinLogBef format [8].

The underlying color coordinate system bef is beneficial for the format. Any equally-spaced decomposition of color space in this CCS has the following properties:

- It is relatively uniform. Measured in McA, linear dimensions of the cells vary less, than 3.43 times. Due to better uniformity, coding in bef may be done with smaller superfluity, than in Lab, RGB or XYZ color coordinate systems, assuming the same provided data accuracy.
- Cells whose indexes differ by 1 are adjacent. This property is beneficial for decorelation.

For color space quantization one should multiply bef coordinates (in floating-point encoding) by a number C and then round the result to the nearest whole. The quantization process is simple in bef and the accuracy provided by the format is determined by a decomposition step, which, in turn, is determined by the parameter C.

Image posterization may be noticeable if distance between a cell's center and a center of any adjacent cell is greater that 1 McA [4]. At $C = C_0 = 239$ the max distance between a cell's center associated with a center of color-matching ellipsoid and centers of 26 adjacent cells is 1 McA, so the decomposition with C = 239 is a frontier between visual lossless and lossy quantization. For the frontier decomposition the max data representation error is Δbef = 0.37.

If $C = C_0$ the average distance between a cell's center associated with a center of color-matching ellipsoid and centers of 26 adjacent cells is 0.56 McA, and the min distance is 0.227 McA. It is easy to see, that the max and the average distance between a cell's center and centers of 26 adjacent to it cells differ less than two times in MacAdam units, so the uniformity of bef based color space decomposition is essentially better than a decomposition usually utilized in image compression.

By varying the parameter C a consumer may set a desired image coding precision. However, the precision adjustment is more convenient to do with a parameter p:

$$C = C_0/p \tag{7}$$

Then the max distance between a cell center associated with a center of color-matching ellipsoid and centers of 26 adjacent cells is p McA and the max data representation error Δbef = 0.37·p. Visual lossless quality corresponds to p = 1.

It is not recommended to use p values outside [0.1, 2] interval.

Comparative testing

To ensure bef format quality, it was compared with two most popular HDR formats implemented in PhotoShop CS3: OpenEXR and Radiance HDR (RGBE). While all major format characteristics were considered, the main attention was paid to precision of color vector representation and compression rate.

The three formats were tested one after another on the same set of HDR images represented in linear-sRGB floating point TIFF (96bpp).

Twenty-eight images were selected for the testing:

- Six images were created in PhotoShop from series of shots made with various expositions and saved as RAW.
- Ten popular HDR images with various scenes (such as Apartment, Golden Gate, and Memorial) were downloaded from Internet. Unfortunately, all those images had insufficient data precision, so we added a small noise (about 1%) to each image to arbitrary fill in the lower order bits.
- Another ten images were created from the previous set by increasing image saturation in order to get pictures with out-of-sRGB gamut colors.
- In addition, we synthesized two HDR images: an image containing all visible colors and an image containing all (and only) sRGB gamut colors.

To calculate a compression rate and the max (for all pixels of an image) error in color vector representation the following procedure was applied to every image:

1. Linear-sRGB floating point TIFF image was converted into compressed HDR image
2. Image compression rate was calculated as an averaged number of compressed bit per pixel
3. The compressed file was converted into linear-sRGB floating point TIFF

4. The file received in the stage 3 was compared pixel by pixel with the initial linear-sRGB floating point TIFF file and the max of color vector deviation (the error in color vector description) was calculated. The color difference was calculated with Δbef (1).

Radiance HDR (RGBE)

In RGBE format coordinates cannot take negative values. This causes errors in HDR image description when a scene has out-of-sRGB gamut colors. For images with out-of-sRGB gamut stimuli, the error in color vector description reaches 72 Δbef. Such images have been excluded from the median error calculation.

For images without out-of-sRGB gamut colors (16 images) the median max error is Δbef = 0.54

The compression rate for RGBE format is 25 bit per pixel (3.8 times file size reduction versus linear-sRGB floating point TIFF)

OpenEXR

The test reveals abnormally high errors (up to 20 Δbef) for some images with high noise level in shadowed areas. Such images have been excluded from the median error calculation.

The median max error (for 16 images) is Δbef = 0.04.

The compression rate for OpenEXR format is 28 bit per pixel (3.4 times file size reduction versus linear-sRGB floating point TIFF)

bef

Format bef provides an option to increase compression rate by reducing data precision. Changing parameter p from 0.1 to 2 leads to two times file size reducing. The performance of format bef is compared with performance of RGBE and OpenEXR and results are presented in figure 1. To create “an equal opportunity” condition for the compression rate comparison, the precision of color vector representation in bef has been varied to meet the precision of the counterpart format.

The bold vertical line in figure 1 at Δbef = 0.37 corresponds to p = 1 and separates lossless and lossy areas. According to the test OpenEXR provides Visual Lossless compression, while RGBE compressed images may have posterization artifacts.

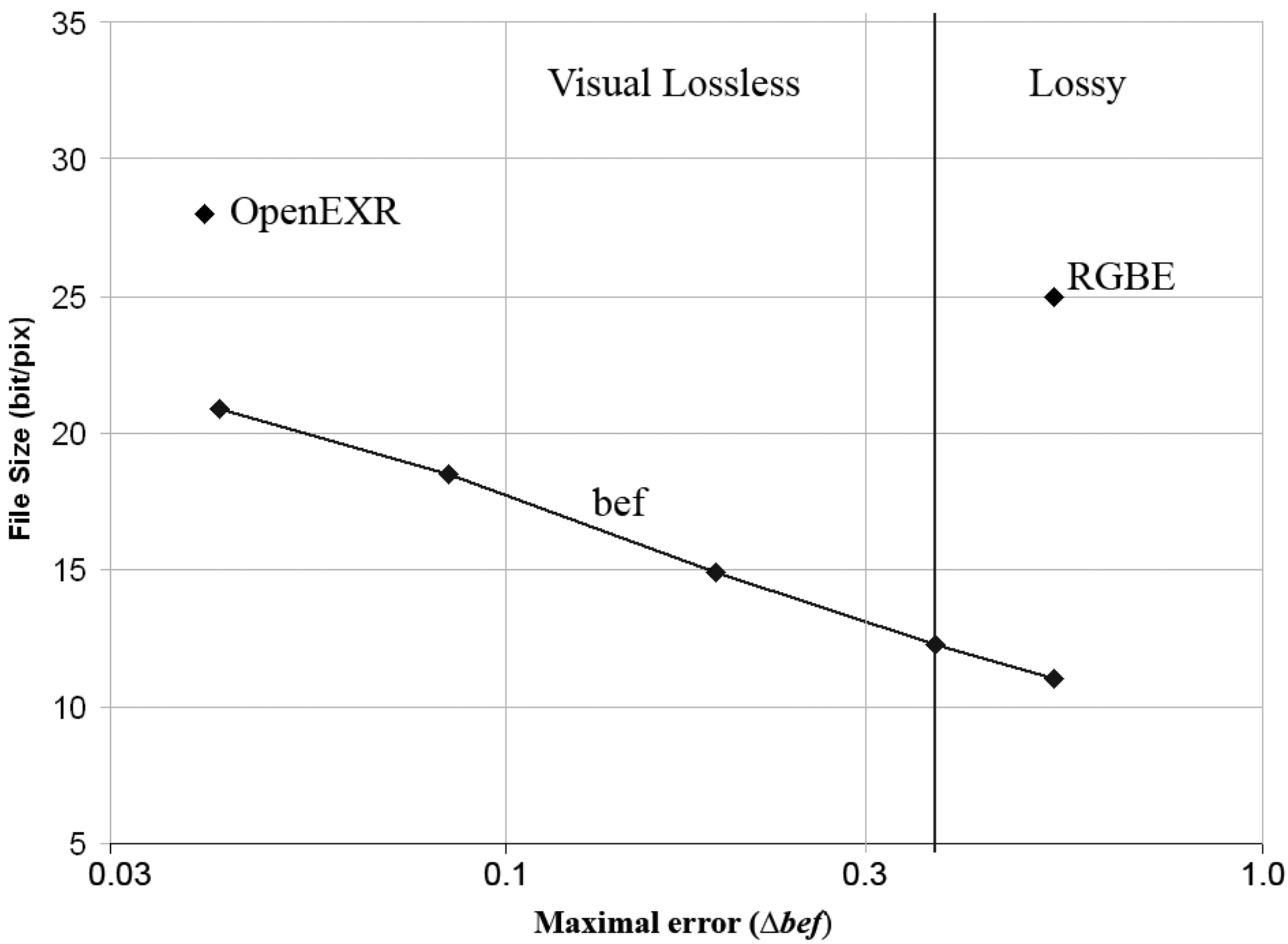

Figure 1. Comparison of average file size and precision for different compression algorithms. The bold vertical line at Δbef = 0.37 *corresponds* to p = 1 and separates lossless and lossy areas.

At p = 1.5 the accuracy of bef format is the same as RGBE accuracy, while the compression provided by bef - 11 bit per pixel (8.8 times file size reduction versus linear-sRGB floating point TIFF) - more, than two times outperforms RGBE.

At p = 0.1 the accuracy of bef format is the same as OpenEXR accuracy, while the compression provided by bef is 20.5 bit per pixel (4.7 file size reduction versus linear-sRGB floating point TIFF), which is 27% better, than OpenEXR's results.

Unlike RGBE or OpenEXR, bef format provides equally good results compressing all 28 test images, what also advantageously distinguish it from both competitors.

Conclusion

Imaging format bef meets all requirements listed in the beginning of this paper. In summary it

- is device independence
- is capable to store all visible colors and images with extremely high dynamic range
- guarantees data precision measured in units based on experimental data on color visual threshold
- achieves the best compression ratio at given precision available today
- offers the tradeoff option for flexible choice of precision versus data size

The range and quality of bef characteristics suggest it may be beneficially used in the area of archiving, especially for HDR imaging.

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