Motion Picture Versioning by Gamut Mapping

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Abstract

Historical frontiers between different content types (motion picture, games, television) and distribution channels (cinema, broadcast, pull services, physical media) are vanishing today. In motion picture production, several products are generated for a single motion picture project, among those the argentic and the digital cinema masters, a DVD master, a trailer and even a video game. Each type or version of the motion picture requires several technical and artistic steps to be done. This paper addresses the management of different color gamuts and proposes to use gamut mapping algorithms as support for color correction in motion picture versioning. In both, manual color correction and gamut mapping, colors are definitively changed. Gamut mapping algorithms can only be a tool to ease artistic work. This paper identifies requirements, reviews existing gamut mapping algorithms and then proposes a toolbox for gamut versioning adapted for motion picture post-production. One of the main requirements is the separate and explicit control of hue, saturation and lightness aspects of color. We propose a new cusp-oriented lightbness mapping that allows a better tradeoff between saturation loss and gamut efficiency. We also describe an enhanced method for automatic estimation of the cusp of a color gamut. A psycho-physical evaluation framework is used to evaluate different combinations of gamut mapping algorithms for motion picture versioning. We specifically analyzed night scenes, animated content, face close-ups, scenes with dominant white portions and general scenes. Results show that the new cusp-oriented lightness mapping enhances the subjective quality of processed versions for most of those scene types.

Introduction

New technologies in capturing and displaying images (multiple exposure, LED backlighting, laser) with extended color gamut and new standards for wide gamut color encoding [7] and distribution [1] enable a new market of extended-color-gamut content (motion picture, sports, news, games, electronic documents).

Historical frontiers between different content types (motion picture, games, television) and distribution channels (cinema, broadcast, pull services, physical media) are vanishing today. In motion picture production, several products are generated for a single motion picture project, among those the argentic and the digital cinema masters, a DVD master, a trailer and even a video game. A motion picture can have a long life and remastering may be needed when content is restored from an old medium.

This paper addresses the scenario of introducing a new extended-color-gamut video master format in motion picture production, post-production and distribution. Main obstacles for this scenario are cost of instruction of a new master format, standardization and compatibility to existing infrastructure. For cost reduction and compatibility, a technical issue is the joint management of standard color gamut and extended color gamut. Manual (high-end) and automatic (consumer) color conversion tools for motion picture content are needed. However, color conversion changes the color of images and can be in conflict with film making as an artwork of the Director of Photography.

One important step in color conversion is gamut mapping. The task of gamut mapping is to map the colors belonging to a source color gamut (for example the extended color gamut of film) into a destination color gamut (for example the color gamut of a standard television monitor). Morovic and Luo [3] give a comprehensive overview on gamut mapping algorithms. Montag and Fairchild [8] as well as Zolliker [9] present comprehensive comparisons and evaluate different approaches.

Gamut mapping always modifies image colors since device constraints have to be met. There is no "zero degradation" method, gamut mapping always impacts an image as artwork. Gamut mapping for automatic color conversion has therefore to be designed considering artistic requirements or it should be only one of the features of a semi-automatic tool that is used by the colorist.

The requirements for motion picture versioning by gamut mapping include:

- Preservation of color neighborhood and order: absence of color banding and false contours;
- Continuity of color: absence of visible quantization or clipping errors;
- Separate control for lightness, hue and saturation: keeping the full artistic control on how colors are modified;
- Signaling: Feedback such as gamut alarm about how colors were mapped [2].

The cusp-oriented color gamut mapping method according to this paper is notably aimed to professional, semi-automatic color conversion tools. The colorist needs to be free to choose any chroma variations, instead of depending on automatic gamut mapping. At least one step of the color conversion should be limited to variations of the lightness with chroma and hue conservation. In a next step of color conversion, the colorist may choose any chroma variations without constraints. A high semantic level of artistic intents is then offered to the colorist thanks to the separate control for lightness, hue and saturation.

In this paper, we address the first three requirements for motion picture versioning. We start with a review of several known gamut mapping algorithms. We then propose two new algorithms for gamut mapping. First, a new tone mapping is derived that is applied before classical gamut mapping. This algorithms is intended to preserve the most brilliant / most saturated colors of a source color gamut (colors close to the cusp of the gamut) and to prevent succeeding gamut mapping algorithms to desaturate them. The tone mapping algorithm exploits the geometric shape of destination *and* source color gamuts. The algorithm requires gamut related metadata about the destination of the image (which is usually available) *and* about the source of the image (which needs to be made available). From a color gamut, the algorithm exploits the cusp lightness. The cusp of a color gamut includes the most saturated colors. The second new algorithm is an enhancement of the cusp estimation method already presented in [13].

This paper presents also a psycho-physical quality evaluation framework based on motion-picture-related quality criteria. We will compare existing methods with a new method.

Review of existing gamut mapping method

Gamut mapping usually requires a **gamut boundary description** (GBD) that defines the boundary of a color gamut. GBDs consist often in explicit, generic 3D representations such as triangle meshes or volume models.

There are three groups of methods for calculating a GBD. *Colorant space methods* require device dependent and independent color coordinates as input. The GBD is calculated by using device dependent coordinates with either minimum or maximum values [15]. *Convex methods* such as the **convex hull method** require as input a more or less exhaustive set of device independent colors belonging to the color gamut. The assumption is that a convex hull includes all these colors. *Non-convex methods* such as modified convex hull [16], alpha shapes and discrete flow complex need the same input data but allow a certain degree of non-convexity.

The **cusp of a color gamut** is the set of colors, where each of these colors has a larger chroma compared to all other colors in the same constant hue leaf of the 3D color space.

The **CUSP clipping** method is one of the so-called chroma clipping or chroma mapping methods and operates in CIELAB like color spaces [6]. The basic method is *straight clipping* where hue and lightness are preserved and all out-of-gamut colors are mapped or clipped into the destination gamut using straight, horizontal mapping trajectories that all aim so-called anchor points lying on the lightness axis. *Straight clipping* reduces only the chroma of colors leading to reduced saturation in resulting images. In *node clipping*, the mapping trajectories aim all a single anchor point lying on the lightness axis at L*=50. In *cusp clipping*, the anchor points are lying on the lightness axis but have the same lightness as the gamut cusp in the hue leaf of the color to be mapped.

The **GCUSP algorithm** from Morovic and Luo [5] consists of an initial chroma-dependent lightness compression followed by CUSP mapping. The degree of lightness compression is high at the achromatic axis and is smoothly decreased as chroma increases.

The **SGCK algorithm** (Sigmodial lightness mapping with GCUSP and Cusp Knee Scaling) is one of the two methods recommended by CIE to be used as reference algorithm in psychophysical tests. This algorithm is a combination of GCUSP, sigmoidal lightness mapping and cusp knee scaling [4,10].

Versioning by gamut mapping

The requirements for gamut mapping of motion picture content are:

- Preservation of color neighborhood and order;
- Continuity of color;
- Separate control for lightness, hue and saturation;
- Signaling (alarms).

Preservation of color neighborhood and order prevents from incoherent reproduction of grey and color ramps. Continuity of colors prevents from banding and false contours. Separate control for lightness, hue and saturation allow the formulation of a higher, semantic level of artistic intents. Signaling is the feedback of the method such as soft gamut alarm [2] to indicate to an operator or control mechanism what happened to the color.

Gamut mapping framework

For motion picture content, we use the gamut mapping framework shown in **Figure 1**. It includes classical color management tools such as source and destination display models. New tools are the cusp estimation and the gamut mapping itself.

The algorithm requires metadata about the destination of the image (destination color gamut) and the source of the image (source color gamut). We represent this metadata explicitly using a 3D triangle mesh, each color is represented by a vertex. The metadata is generated by a convex hull method in CIEXYZ color space but gamut mapping is carried out in CIELAB color space.

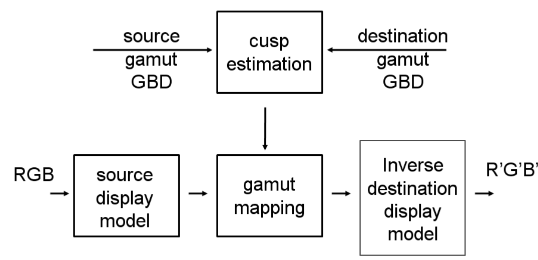


Figure 1*. Framework of the new gamut mapping algorithm*

This paper has two algorithmic contributions: First, an enhanced cusp estimation algorithm and second a new, cusp-oriented tone mapping algorithm. Both algorithms are described further down in dedicated sub sections.

Estimation of the cusp of a color gamut

We assume that the cusp of a color gamut has to be estimated from the Gamut Boundary Description (GBD). The GBD is represented by a not always convex 3D triangle mesh in CIELAB color space. The problem of cusp estimation is then to identify the polygon inside the GBD mesh that represents the cusp of the gamut.

We use a simple incremental search algorithm in CIELAB from [16] using the following steps:

1. A first cusp vertex of the GBD is identified having the highest saturation $C^* = \sqrt{a^{*2} + b^{*2}}$ with a* and b* being CIELAB coordinates.

2. A neighboring vertex is identified as next cusp vertex if a quality criterion (definition see further down) is maximal.
3. Step 2 is repeated until the cusp polygon is closed or turned around 360 degrees.

The quality criterion is a combination of five criteria. The saturation, lightness similarity, hue angle increase and collinearity criteria C_S, C_H, C_I, C_D [16] are calculated as follows:

$$C_S = \frac{C^*(1+D/c_2)}{c_1} \quad ; \; C_I = 1 - \frac{\left(L^* - \widehat{L}^*\right)^2}{(c_3)^2}(1+D/c_2)$$

$$C_H = \frac{\alpha_H - \widehat{\alpha}_H}{c_4} \; ; \; C_D = 1 - \alpha_D / c_5$$

with c_1, c_2, c_3, c_4, c_5 being constant parameters, D is the distance between the current and a neighboring vertex, $\widehat{L}^*$ and L^* the lightnesses of the current and a neighboring vertex, respectively, $\widehat{\alpha}_H$ and α_H being the hue angles of the current and a neighboring vertices, respectively, α_D being the angle between the difference vectors d and $\widehat{d}$, d being the difference vector between the current and a neighboring vertex and $\widehat{d}$ being the difference vector between the current and the previous cusp vertices.

A new, fifth criterion, the curvature criterion C_C is proposed in this paper. It aims to identify cusp colors that lie on a sharp rim of the gamut assuming that here are the most sat6urated colors. It is based the angle α_C between GBD surface normals measured on the "left" and "right" side of a cusp edge candidate. The cusp edge candidate is the edge built by the current and a neighboring vertex. From this angle, the curvature criterion $C_C = 1 - c_6 / \alpha_C$ is calculated with c_6 a constant parameter.

The quality criterion C is calculated for a neighboring vertex by a weighted sum according to

$$C = c_S C_S + c_H C_H + c_I C_I + c_D C_D + c_C C_C$$

with constant weights c_S , c_H , c_I , c_D and c_C .

Cusp-oriented tone mapping

The cusp information is then used for tone mapping in a different way compared to existing algorithms. The GCUSP algorithm for example uses the destination color gamut cusp lightness to choose the anchor point, the ending point of a mapping trajectory. In opposite to GCUSP, so-called cusp to cusp mapping algorithms adapt the entire mapping trajectory in a way that source primary cusp colors are mapped to destination primary cusp colors. In opposite to known cusp-to cusp mapping, we define an isolated tone mapping operator that is based on the following characteristics:

- Keeping hue constant to preserve the artistic intent;
- Lightness compression towards the cusp lightness, the lightness compression using a chroma dependency factor.

The tone mapping is defined independently for each hue leaf of the source color gamut assuming smooth gamut shape. In each leaf, the cusp colors of the source and destination gamuts are identified. Furthermore, the black and white points ot the two gamuts are supposed to be known. A tone mapping function $f(\bullet)$ is defined according to the following four criteria:

First criterion: A color having the lightness $L^{*SOURCE}_{CUSP}$ of the cusp of the source gamut is mapped to a color having the lightness L^{*DEST}_{CUSP} as the cusp of the destination gamut. According to this first criterion, the tone mapping function satisfies:

$$f\left(L^{*SOURCE}_{CUSP}\right) = L^{*DEST}_{CUSP} .$$

Second criterion: A color having the lightness $L^{*SOURCE}_{BLACK}$ of the black point of the source gamut is mapped to a color having the lightness L^{*DEST}_{BLACK} as the black point of the destination gamut. According to this second criterion, the tone mapping function satisfies:

$$f\left(L^{*SOURCE}_{BLACK}\right) = L^{*DEST}_{BLACL} .$$

Third criterion: A color having the lightness $L^{*SOURCE}_{WHITE}$ as the white of the source gamut is mapped to a color having the lightness L^{*DEST}_{WHITE} of the white point of the destination gamut. According to this third criterion, the tone mapping function satisfies:

$$f\left(L^{*SOURCE}_{WHITE}\right) = L^{*DEST}_{WHITE} .$$

Forth criterion: The tone mapping functions $f_1(\bullet)$ and $f_2(\bullet)$ of two colors having the chroma values $C_1{}^*$ and $C_2{}^*$, respectively, having both the same lightness $L_1{}^* = L_2{}^* = L^*$, and having the same hue satisfy:

$$\frac{f_1(L^*)}{f_2(L^*)} = \frac{C^*_1}{C^*_2} .$$

The fourth condition ensures that colors with small chroma values are less mapped than colors with large chroma values. In this way, grey ramps near the L* axis are preserved.

For the tone mapping function, we use a piecewise linear model according to:

$$f(L^*) = aL^*$$

with a being a piecewise linear lightness factor that is defined as follows:

$$a = bc\frac{L^{*DEST}_{CUSP}}{L^{*SOURCE}_{CUSP}} + (1-bc)$$

and b being a piecewise linear weight that is defined as follows:

$$b = \begin{Bmatrix} \dfrac{L^* - L^{*SOURCE}_{BLACK}}{L^{*SOURCE}_{CUSP} - L^{*SOURCE}_{BLACK}} & if \quad L^* \le L^{*SOURCE}_{CUSP} \\ \dfrac{L^{*SOURCE}_{WHITE} - L^*}{L^{*SOURCE}_{WHITE} - L^{*SOURCE}_{CUSP}} & if \quad L > L^{*SOURCE}_{CUSP} \end{Bmatrix}$$

and c being piecewise linear chroma dependency factor that is defined as follows:

$$c = \min\left\{1 \quad ; \quad \frac{C^*}{C^{*SOURCE}_{CUSP}}\right\}$$

with C* the chroma of the color to be mapped and $C^{*SOURCE}_{CUSP}$ the chroma of the source gamut cusp.

Evaluation method for gamut mapping

The performance of gamut mapping can be investigated using objective and/or subjective criteria. For example, Zolliker et al. [9] propose an objective test procedure to evaluate local color continuity. In the context of use for post-production, we decided to use subjective tests. The CIE [10] developed an evaluation framework for gamut mapping algorithms including a set of test images, media, viewing conditions, measurement methodologies and benchmark algorithms. For example, the CIE recommends the use at least one specific test image, the "Ski" image (www.colour.org/tc8-03). We included this image in sRGB encoding in our test set. The CIE further recommends two reference algorithms for benchmarking: hue preserving minimum ΔE clipping [11] and SGCK [10]. However, we do not use them for the following reasons: Hue preserving minimum ΔE clipping shows low performance [12] and SGCK includes sigmoidal lightness mapping that is not adapted for post-production applications where the white luminance is not changed.

Wide color gamut image corpus

We generated a large test corpus of Wide Color Gamut (WCG) images by color grading on a WCG display. We carried out a subjective test on color preference in order to select finally 10 subjectively acceptable WCG images. The test images include the "Ski" image and 9 critical examples from motion picture production such as outdoor, indoor, night, white-dominated scenes, animations, close-ups and facial images.

Test method

We developed a test method different from the CIE [10] in order to address the following requirements:

- Minimize the bias in evaluation caused by color difference of color gamuts of displays;
- Evaluation of impact on different aspects of color.

Gamut mapping always alters colors when the destination color gamut is smaller than the source color gamut. We want to design a test method that prevents from negative evaluation results only due to this. We also want to evaluate the impact on different aspects of color such as hue, saturation, contrast, white temperature and memory colors.

In order to satisfy the requirements, our test method is characterized by the following:

- Gamut mapped images are judged with respect to original images (original colors are the reference);
- Use of side-by-side butterfly representation on a single display using proof-viewing (in order to exclude display characterization errors);
- Two gamut mapping methods are pair compared in temporal order (in order to lower the bias from the pure difference of display gamuts);
- Absolute quality scale instead of impairment scale (enabling simple test exploitation); The scale goes from 1 (bad) to 5 (excellent);
- Observer are focused on specific objects in images (allowing a tight test procedure);
- Focus on specific color aspects (hue, saturation, skin color or white**).**

Two butterfly images generated by two different gamut mapping methods are presented in temporal order according to **Figure 2**.

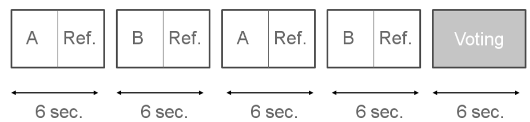


Figure 2*. One test cell comparing methods A and B with respect to the original*

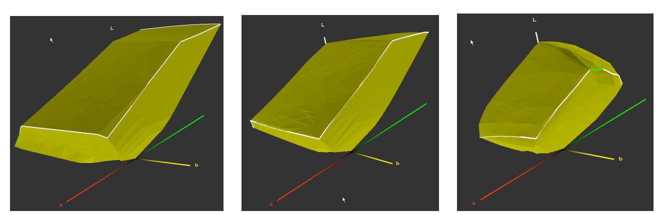
We invited 15 persons to a first test and a subset of 8 persons to a second and third test. The test persons have general skills in image processing and the subset of 8 persons has even skills in color science. For the first test, we conducted 60 pair comparisons for each person involving six test images. For the second and third tests, we conducted 40 pair comparisons for each person involving 4 test images.

Results

In this section, we present results of cusp estimation and gamut mapping. For cusp estimation, the weights were chosen as follows for all experiments:

$$c_S = 0.5,\ c_I = 1.0,\ c_H = 0.7,\ c_D = 0.4, \text{ and } c_C = 0.5.$$

Cusp estimation has satisfactory performance for a large variety of gamuts including mathematically perfect standard gamuts (**Figure 3**a), measured, approximately additive gamuts (**Figure 3**b) and even subtractive gamuts (**Figure 3**c).



(a) **(b)** **(c)**

Figure 3. *Estimated cusps in CIELAB space (white line) for three color gamuts:*
(a)standard TV production monitor according to EBU requirements [14],
(b) LCD LED backlight wide color gamut display, and
(c) positive 35mm film printing and projection

In **Figure 4** can be seen that the incremental search algorithm for cusp segments may go wrong when passing a very saturated primary or secondary color (**Figure 4** left). The new surface curvature criterion keeps the algorithm on the rim even if the cusp polygon proceeds to less saturated colors (**Figure 4** right).

Figure 4. Estimated cusp (white line) without (left) and with (right) surface curvature criterion for an EBU display

In order to investigate gamut mapping, images have been mapped from a wide color gamut (WCG) display to a standard Rec. 709 display. The WCG display is an HP 24" LCD display “Dreamcolor” with RGB LED backlight and 1920x1080 resolution, while the standard display is a Philips 37" LCD screen with CCFL backlight and 1920x1080 resolution.

In our experiments, three known methods and the new cusp-to-cusp mapping are compared. The four methods are summarized in ***Table 1*** and have the following characteristics:

1. **Straight clipping**: nearly-straight CUSP clipping with anchor points being inside 5% to 95% of the of lightness axis.
2. **Straight linear scaling:** Derived from straight clipping, but clipping is replaced by scaling. All colors inside the source color gamut are linearly scaled into the destination gamut instead of being clipped; we expect to better preserve image details with respect to straight clipping.
3. **Straight non-linear scaling:** Same as second method but compression is non-linear with a kernel of preserved colors of low chroma; we expect to better preserve skin tones.
4. **New cusp-to-cusp mapping:** Similar to the third method but using additionally the new cusp-oriented tone mapping is applied before straight non-linear scaling; we expect to preserve better most saturated colors compared to the third method.

Table 1: Tested gamut mapping methods

Characteristics of method	Straight clipping	Straight linear scaling	Straight non-linear scaling	New cusp-to-cusp mapping
Lightness compression towards the cusp lightness	No	No	No	Yes
Color space for mapping	CIELAB	CIELAB	CIELAB	CIELAB
Straight mapping/clipping	Yes	Yes	Yes	Yes
Chroma compression	Clipping	Linear	Non linear	Non linear
Use of source gamut	No	Yes	Yes	Yes

The fourth method that involves the new cusp-oriented tone mapping is intended to preserve the most brilliant (i.e. most saturated) colors of an image. After mapping the lightness, the following classical gamut mapping will preserve the saturation of these colors by placing them into the cusp region of the destination gamut.

Table 2 shows the mean scores and standard deviations obtained by the three subjective tests. The first, most important test involves a variety of test images in order to evaluate quality of hue and saturation. It can be seen that the linear scaling method does not perform well. The reason is too much loss of saturation all over the color gamut. Clipping and non-linear scaling methods have scores that are close to each other thanks to the better preservation of saturation in the core of the color gamut. Additionally, non-linear scaling preserves image details with respect to clipping. Best method is the new cusp-to-cusp mapping that involves the new tone mapping. It preserves saturation of most brilliant colors while lightness changes are tolerated by the observers. The standard deviations show that the results are clear (standard variation lower than 0.4) for straight linear scaling (bad score of 1.93) and the new cusp-to-cusp mapping (good score of 2.73). Less clear (standard deviations larger than 0.6) are the straight clipping and non-linear scaling methods that sometimes produce good and sometimes bad results. The individual scores for hue and saturation, respectively, are very close to each other. This shows that it is difficult to independently judge these color aspects in a test with limited observation time (6 seconds each for comparison and voting).

For the second and third tests, the test images include face close-ups (skin color) and scenes with large white portions (snow, buildings), respectively. Neither skin color nor white tones are highly saturated. The change of lightness introduced by the new cusp-to-cusp mapping is perceived as disturbing and gets worse scores compared to the other methods. This is not surprising and a colorist should not choose this method for such specific images.

Table 2: Psycho-physical evaluation results of first, second and third tests

Test	**Evaluated color feature**	**Image content**		Straight clipping	Straight linear scaling	Straight non-linear scaling	New cusp-to-cusp mapping
1	Hue, sa-turation	Large variety	**Score**	**2.40**	**1.93**	**2.30**	**2.73**
			Std.dev	0.63	0.39	0.61	0.33
2	Skin color	Large face portion	**Score**	**4.40**	**2.95**	**4.39**	**4.12**
			Std.dev	0.24	0.92	0.22	0.40
3	White	Dominant whites (snow, buildings)	**Score**	**4.64**	**3.38**	**4.65**	**3.57**
			Std.dev	0.26	0.75	0.27	0.86

Figure 5 shows a typical result for the “Ski” image where the preservation of saturations in the red tones is visible. The reader should note that the images in this paper are calculated in the RGB space of the HP WCG display. The color differences are distorted when reproduced on paper or on computer screens. However, we verified the visibility of most of shown color differences on Rec. 709 LCD displays and high quality sRGB computer LCD screens. **Figure 6** shows an example of painting like or animated content. Since colors are often highly saturated, the benefits of the new cusp-to-cusp mapping are easily visible. **Figure 7** shows an example of a night scene in downtown where often highly saturated colors occur. For other test images with natural indoor and outdoor scenes, scores are still significantly better but the color difference are poorly visible when this paper is not reproduced on a WCG display.

***Figure 5**. Close-up of butterfly test image “Ski” straight- clipping method (left) and for the new cusp-to-cusp mapping (right)*

***Figure 6**. Close-up of butterfly test image “painting” for straight- clipping method (top) and for the new cusp-to-cusp mapping (bottom)*

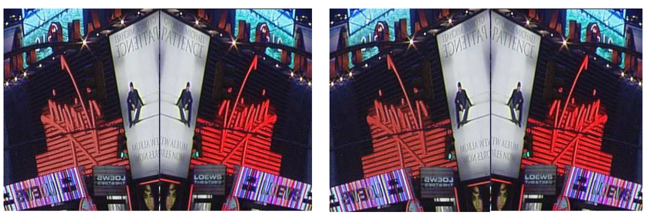


***Figure 7**. Close-up of butterfly test image “night in downtown” for straight-clipping method (left) and for the new cusp-to-cusp mapping (right)*

Conclusions

We developed a new gamut mapping framework for motion picture using classical color management tools (source and destination display models) as well as new tools: color gamut cusp estimation and lightness mapping towards the cusp lightness. We also developed a psycho-physical evaluation framework having less bias caused by choice of used display gamuts and allowing evaluation of aspects of color such as hue, saturation, whites and skin color. In comparison to known methods (clipping, linear scaling and non-linear scaling), the new gamut mapping framework performs significantly better, notably for images with saturated colors such as outdoor night scenes and animated content.

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Laurent Blondé is graduate engineer of the Institut d’Optique - ParisTech (1985). Hired as a research engineer for Technicolor Research & Innovation (formerly Thomson), he participated in more than a few R&D projects including: Infrared Image Synthesis, Special Effects and Virtual Studio, Display processing, Anti-Camcorder and Color Management for Cinema applications. Supporting Technicolor businesses, Laurent Blondé is currently a Principal Scientist. His research interests involve all domains of image processing for the media industry, with physics and perception in mind.