# Boosting Luminance of a Colour-Sequential Display

*M. Hammer, K.J.G. Hinnen, and E.H.A. Langendijk*

*TP Vision Netherlands, 5656 AE Eindhoven, the Netherlands*

## Abstract

***The dynamic range of many real-world environments greatly exceeds the dynamic range of display systems based on liquid-crystal (LC) panels. Using a matrix of locally-addressable high-power LEDs, both the black level and the brightness can be improved. In this contribution, we describe a method for boosting luminance without installing additional light. The method is applicable to colour-sequential displays. We also validate the performance of the solution in terms of average luminance gain on a large set of video data. The results show an average luminance increase of 143% for 240 backlight segments.***

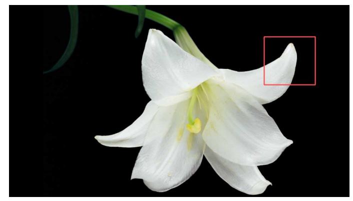
## Introduction

In the past decade numerous research activities have focused on the difference between the dynamic range of real-world environments and the dynamic range characteristics of state-of-the-art display systems. Common display systems such as LCDs are not capable of reproducing the pitch-black of a night scene or the extreme brightness seen on a sunny day.

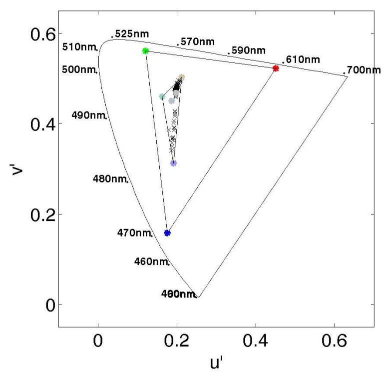
Black-level reduction by orders of magnitude has been achieved with local dimming backlights, which use a matrix of locally-addressable LEDs to adjust the backlight intensity to the image. However, high brightness displays are commonly designed by simply installing more light. [1] As additional light requires more, or more powerful, LEDs, the bill-of-material goes up. In this contribution, we describe a novel method for boosting luminance without installing additional light. The method is in particular applicable to colour-sequential displays.

Colour-sequential display systems based on liquid-crystal (LC) panels, have caught considerable attention as they potentially eliminate the efficacy losses due to the colour filters. Without the colour filters and using a flashing backlight of red, green, and blue primary colours, for example using LEDs, it is potentially three times more efficient than a regular colour-filter based LCD [4, 5, 6]. However, the temporally flashing behaviour of colours lead to annoying colour breakup artefacts in case of (fast) eye movements. At high refresh rates, colour breakup is reduced and imperceptible to the human observer, but due to the slow temporal response of LC-panels, colour breakup remains an obstacle for the commercial breakthrough of colour-sequential systems based on LC-panels.

Advances in video processing have greatly reduced the presence of colour breakup [2, 3, 7, 8]. The proposed concepts are based on an advanced backlight with a matrix of red, green, and blue LED triplets which are locally addressable. Based on the video content, the backlight primaries are locally adjusted to reduce the colour differences between the primaries, thereby reducing the resulting colour breakup.



(a)




(b)

***Figure 1.*** *(a) Input image for the illustration of local primary desaturation for a colour-sequential display system. The area in the red box is the segment under consideration. (b) CIE 1976 $u'v'$ coordinates of the reference gamut (Rec. 709), the new local gamut, and the pixels in the red box show in (a).*

In this paper we propose a method to increase the luminance of a colour-sequential display system. For a traditional 3-field colour-sequential system, luminance can be boosted with up to a factor three. In the following section we review related work on local dynamic gamuts for colour sequential displays. We then introduce the concept of local luminance boosting. In the subsequent section, we illustrate the performance of the proposed method. Finally, we investigate the potential increase of luminance across a large set of video data in order to understand how often and how large luminance gain one can expect to achieve.

### *Related Work*

Traditional colour-sequential displays are based on forming colours by sequentially flashing the primary colours red, green, and blue in three separate fields. To address the issue of colour-breakup Lin *et. al* [2] and Zhang *et. al* [3] proposed to reduce the colour differences between the fields by adjusting the colour of the primaries. This is achieved by flashing combinations of the red, green, and blue colours in each field. The new primaries

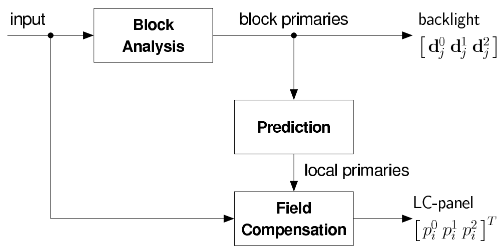



***Figure 2.*** *A flow chart of local primary desaturation for a colour-sequential display system with a backlight comprising a matrix of locally-addressable coloured LEDs.*

are subject to form a gamut volume which is sufficiently large to encompass the image content.

In order to illustrate the concept of a local dynamic gamut, consider the input image of Figure 1(a). The segment in question has been marked with a red box. It is assumed that the input image and the display system are defined by the Rec. 709 primaries. By segmenting the backlight into smaller areas, we intend to reduce the (local) gamut in such a way that it just covers the range of chromaticities present in the image. In Figure 1(b) the CIE 1976 $u'v'$ chromaticity coordinates of the pixels in the red box of Figure 1(a) are shown as black dots. By applying local-primary desaturation, the new primaries are computed which creates a smaller gamut [2, 3]. This smaller gamut is also indicated in Figure 1(b)

We will now define the forward model of a 3-field colour-sequential display system. Throughout the paper we assume a segmented backlight comprising a matrix of locally-addressable LED triplets. Let the $3 \times 3$ matrix $\mathbf{A}$ represent the tri-stimulus values for the red, green, and blue LEDs measured through the LC-panel. The three drive levels for each field, $f \in \{0,1,2\}$, in the $j^{\text{th}}$ segment are denoted by $0 \leq \mathbf{D}_j^f \leq 1$ and $\mathbf{D}_j = \left[\mathbf{d}_j^0 \ \mathbf{d}_j^1 \ \mathbf{d}_j^2\right] \in \mathbb{R}^{3\times3}$. The transmission levels of the panel, $0 \leq p_i^f \leq 1$, is defined by $\mathbf{p}_i = \left[p_i^0 \ p_i^1 \ p_i^2\right]$ for the $i^{\text{th}}$ pixel. Then the tri-strimulus output of the display is:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \mathbf{A}\mathbf{D}_j \mathbf{p}_i \,. \qquad (1)$$

In its most simple form, the fields of a colour sequential display are formed by a spatially uniform red, green, and blue backlight corresponding to $D_{\text{RGB}} = \mathbf{I}_3$. The gamut covered by this solution is given by the primaries of $\mathbf{A}$. With local-primary desaturation the primaries of $\mathbf{A}$ are mixed as the off-diagonal of $\mathbf{D}_j^f$ is allowed to be non-zero. The smallest possible gamut is formed by identical columns of $\mathbf{D}_j^f$, which means that each field has the same chromaticity, for example all white or all red.

A flow chart for local-primary desaturation is shown in Figure 2. The input image is divided into blocks corresponding to the segmentation of the backlight. For each block, the primaries are desaturated to create a small gamut area (if possible). The resulting drive signals for the backlight segments are used to predict the amount of light falling onto the LC-panel. This will form the local per-pixel primaries. In the prediction of the per-pixel primaries, the point-spread function of each segment is taken into account. Let the relative amount of light from the $j^{\text{th}}$ segment on the $i^{\text{th}}$ pixel be given by $0 \leq h_{i,j} \leq 1$, then the forward model, including the point-spread function, is:

$$\hat{\mathbf{o}}_i = \left( \sum_{j=0}^{N-1} \mathbf{A}\mathbf{D}_j h_{i,j} \right) p_i \,, \qquad (2)$$

for a system with $N$ pixels and where $\hat{\mathbf{o}}_i = \left[\hat{X}_i \ \hat{Y}_i \ \hat{Z}_i\right]^T$. As the backlight segments may differ in drive signals (and therefore in primaries), the inter-segment cross-talk may affect the local primaries. It is therefore advantageous to reduce the intensity of each local primary to a minimum, in order to reduce the influence on the chromaticity of neighbouring segments.

The effect of reducing the intensity of the local primaries can be illustrated by observing Figure 3. The figure shows a side view of a gamut volume showing luminance as a function of the CIE 1976 $v'$ chromaticity coordinate. The black dots represents the pixels of the segment in the red box indicated in Figure 1(a). The reference gamut is shown in red-solid and the de-saturated gamut is shown in blue-dotted. Notice that both the reference and the desaturated gamut are too large. It is therefore possible to reduce the intensity of the backlight in all fields. This operation is similar to local dimming for a system with a white backlight, however, it is also possible to reduce the intensity of each field independently and thereby skew the local gamut and obtain the smallest possible volume which do encompass all pixels.

In order to achieve the correct colour for each pixel, the transmission levels of the LC-panel for each field, $\mathbf{p}_i$, must be computed. This can for example be done with quadratic programming as in:

$$\underset{0 \leq \mathbf{p}_i \leq 1}{\operatorname{argmin}} \left\| \mathbf{t}_i - \left( \sum_{j=0}^{N-1} \mathbf{A}\mathbf{D}_j h_{i,j} \right) \mathbf{p}_i \right\|^2 , \qquad (3)$$

where $\mathbf{t}_i$ is the target tri-stimulus value for the $i^{\text{th}}$ pixel. As a faster alternative, we found that employing the pseudo-inverse of the local primaries in combination with soft-clipping to work well.

In order to illustrate the principles of local primary desaturation, we have processed the image of Figure 1(a). We assumed

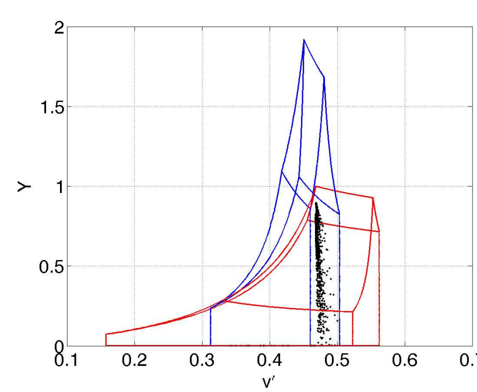



***Figure 3.*** *Side view of the gamut volume of regular colour-sequential mode (red-solid) and the de-saturated gamut volume (blue-dotted) for the segment indicated in Figure 1(a). The gamut volumes are seen from CIE 1976 v′ and luminance.*

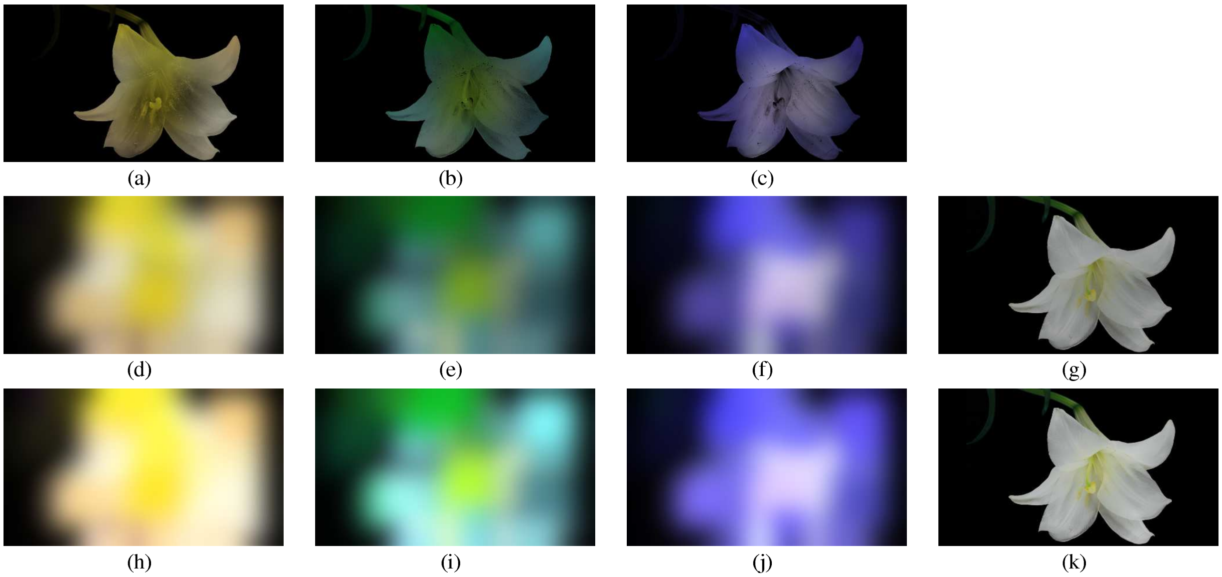



***Figure 4.*** *Illustration of the front-of-screen image for the three fields (top row, a-c) and the corresponding backlight image with (bottom row, h-j) and without (middle row, d-f) boosting. The resulting front-of-screen image is seen in the last row with (k) and without (g) boosting.*

a backlight with a segmentation of 20 by 12 (240 segments). The spatial profiles of the segments were defined by a Gaussian profile. The local primaries were computed based on the chromaticity of the pixels below the segment in question and the immediate neighbours (9 segments in total). The area over which pixels are taken into account is larger than the segment in order to take the inter-segment cross-talk into account and prevent excessive clipping. We applied image pre-filtering in order to reduce noise and remove chromaticity distribution outliers.

Applying the outlined method results in the image shown in Figure 4(g). The corresponding fields of backlight modulated with the LC-panel, are shown in Figure 4(a), 4(b), and 4(c). The three fields showing the backlight only are shown in Figure 4(d), 4(e), and 4(f). Notice how the local primaries appear desaturated, the lack of saturated red, and how frequent white occurs as a local primary. Also notice how the backlight appears dark in regions where the image is black.

As illustrated in Figure 3, it is important to reduce the intensity of the local primaries. The gamut volume should be made small while still large enough to contain the pixels. However, if one would not reduce the intensity of the desaturated primaries which form the blue gamut volume, it would be possible to represent pixels at luminance levels considerably higher than the reference system (red gamut volume). In other words, it would be possible to increase the luminance of those pixels above the maximum luminance of the reference system. In the following section we describe how we approach this local tone-mapping problem of increasing the brightness of pixels in areas were the gamut volume allows.

## Boosting Method

The potential increase of luminance boosting will now be quantified. Consider a white region, similar to the petals of the lily of Figure 1(a), but with an even more limited set of chromaticity coordinates. Starting with the reference gamut and step-wise desaturating the primaries towards white, will result in a gamut as shown in Figure 5(a). If we consider the maximum intensity of white for the new gamut compared to the reference gamut, this gives an indication of the potential luminance gain. We show the resulting curve (black-dotted) as a function of the gamut coverage in Figure 5(e). The gamut coverage is the ratio of the area of the new gamut compared to the area of the reference gamut expressed in CIE 1976 $u'v'$. We observe that the maximum gain is 3 and the minimum is 1. It is also clear, that if it would be possible to reduce the size of the gamut to less than 20%, one would have 50% additional luminance.

In a similar way one can consider an all-red image. If the gamut consists of three red fields, rather than a red, a green, and a blue field, the luminance gain would be 3. In Figure 5(e) the resulting gain-curve is shown (red-solid). Similar for green (green-dashed) and for blue (blue-dash-dotted). It can be observed that the gain factor depends on the chromaticity of the target. This is caused by the relationship between the amount of primary desaturation expressed as the gamut coverage w.r.t. the reference gamut. But, it is also caused by the difference between a target chromaticity in the gamut white-point (all fields transmissive) and a target chromaticity equal to one of the primaries. As both the size of the desaturated gamut and the target chromaticity affects the luminance gain, it is difficult to generalise this theoretical quantification of the luminance gain.

To utilise the boosting capabilities of colour-sequential display systems based on local primary desaturation we provide the flow chart of Figure 6. The block analysis is similar to the method described in the previous section resulting in small(er) local gamuts and the intensity of the primaries reduced. First of all, headroom should be created to allow boosting of the pixels. Secondly, the pixels should be tone mapped depending on the available headroom. For this we provide the blocks *backlight boost* and *pixel boost*.

If one simply increases the intensity of the backlight primar-

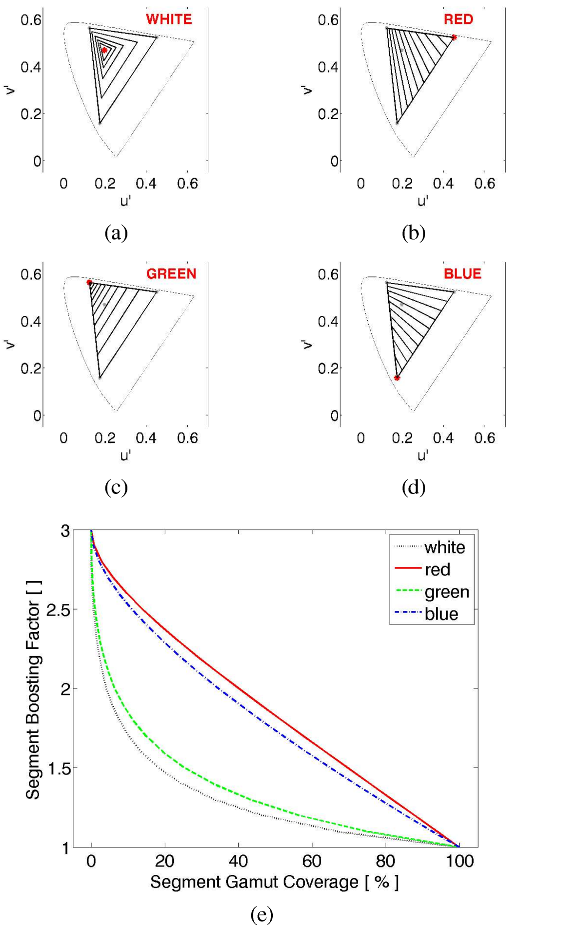



***Figure 5.*** *Illustration of step-wise desaturation towards a white-only gamut consisting of three white fields is seen in (a). In (e) luminance gain for a white (black-dotted) target chromaticity as a function of gamut coverage expressed as a CIE 1976 $u'v'$ ratio. Step-wise desaturation towards a red, a green, and a blue gamut is shown in (b), (c), and (d), respectively. The corresponding luminance gain for red (red-solid), green (green-dashed), and blue (blue-dash-dotted) is shown in (e).*

ies to the maximum possible, black regions, where the local dimming step has contributed to a reduced black level and increase contrast, will be undone. We therefore alternatively propose to only increase the intensity of primaries which are already considerably bright. In order to preserve the chromaticity of the primaries, we modify the backlight drive level of the $j^{\text{th}}$ segment in the $f^{\text{th}}$ field to:

$$\tilde{\mathbf{d}}_j^f = \frac{g\left(\max\left(\mathbf{d}_j^f\right)\right)}{\max\left(\mathbf{d}_j^f\right)}\mathbf{d}_j^f\,, \tag{4}$$

where the boosting function, $g(x)$, is defined by:

$$g(x) = \begin{cases} x/c, & x \leq c\,, \\ 1, & x > c\,. \end{cases} \tag{5}$$

Note that $0 \leq x \leq 1$, such that, $0 \leq g(x) \leq 1$. The constant, $0 \leq c \leq 1$, defines the level of boosting. Applying Eq. (4) leads to a taller gamut with the same chromaticity coordinates, but headroom for increasing the luminance of the input signal. If nothing else is changed, the resulting output would be exactly the same as without the boosting, due to the field compensation. In order to benefit from the headroom, the input image should be tone mapped taking into account the headroom.

## Conditional Tone Mapping

We have shown that the luminance increase depends on the desaturated gamut and on the target chromaticity. A simple method of tone mapping could consist in using the ratio of the reference gamut luminance (height) and the desaturated gamut luminance (height) at the target chromaticity. We show how to compute this per-pixel gain value. Let the maximised LC-panel drive level of the $i^{\text{th}}$ pixel be given by, $\mathbf{p}_i^{\max} = \frac{\mathbf{p}_i}{\max(\mathbf{p}_i)}$. Then the maximum luminance for the corresponding chromaticity coordinate in the desaturated gamut can be defined as:

$$Y_i^{\max} = [\,Y_{\mathrm{R}}\;\; Y_{\mathrm{G}}\;\; Y_{\mathrm{B}}\,]\left(\sum_{j=0}^{N-1}\tilde{\mathbf{D}}_j\, h_{i,j}\right)\mathbf{p}_i^{\max}\,, \tag{6}$$

where $\tilde{\mathbf{D}}_j \in \mathbb{R}^{3\times 3}$ is the boosted backlight signal of the $j^{\text{th}}$ segment. The vector $[\,Y_{\mathrm{R}}\; Y_{\mathrm{G}}\; Y_{\mathrm{B}}\,]$ is the second row of the primary matrix, $\mathbf{A}$. The maximum luminance of the reference gamut, $Y_i^{\max-\mathrm{ref}}$, can be computed by replacing the backlight signal with the identity matrix. We define the per-pixel gain, $g_i$, as the ratio of $Y_i^{\max}$ and $Y_i^{\max-\mathrm{ref}}$.

As it turns out, the per-pixel luminance headroom can vary considerably. This leads to large, high-frequency variations in the tone-mapped output. The strong dependence on chromaticity can also lead to undesirable changes in colour appearance. This problem can be reduced with low-pass filtering and other signal processing tricks. Instead, we have circumvented the problem by taking a different approach.

We first compute the actual headroom for each pixel in a segment at block level, that is, before taking the inter-segment cross-talk into account. The maximum luminance at block-level can be computed as:

$$\tilde{Y}_i^{\max} = [\,Y_{\mathrm{R}}\;\; Y_{\mathrm{G}}\;\; Y_{\mathrm{B}}\,]\,\tilde{\mathbf{D}}_j \mathbf{p}_i\,. \tag{7}$$

The per-pixel headroom is given by $\frac{\tilde{Y}_i^{\max}}{\tilde{Y}_i^{\max-\mathrm{ref}}}$. We then average the headroom across all pixels in this segment and use this as the desired boosting factor. This may lead to an underutilised system for some pixels (above average headroom), while other pixels

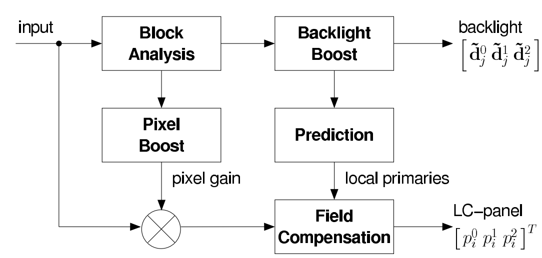



***Figure 6.*** *A flow chart of local primary desaturation with luminance boosting. Compared to the basic flow chart (Figure 2), two blocks has been added.* Backlight boost*, which creates headroom where available, and* pixel boost*, which does per-pixel tone mapping.*

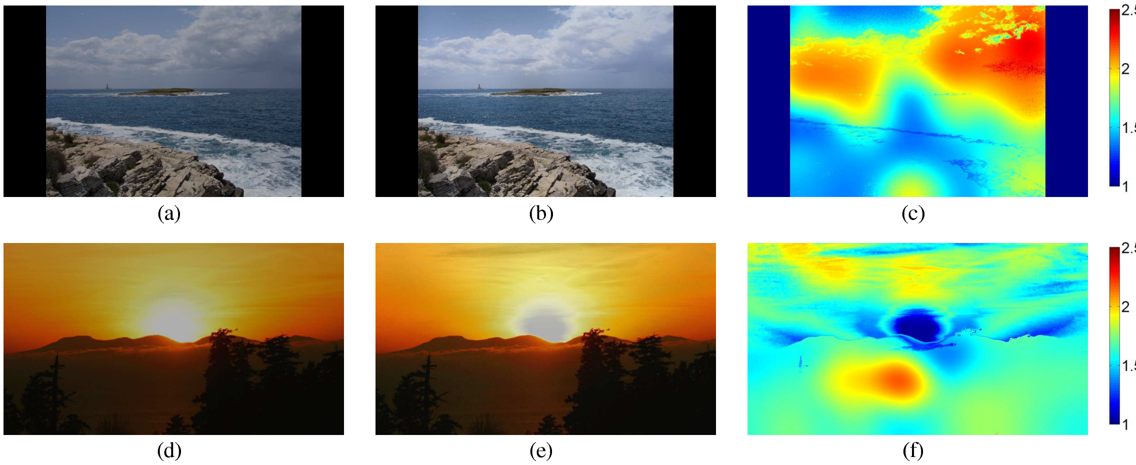



***Figure 8.*** *Illustration of the front-of-screen image with (b,e) and without (a,d) boosting. The corresponding luminance gain maps are seen in (c) and (f), respectively.*

will be subject to clipping (below average headroom). One could also employ the minimum, maximum, or 90$^{\text{th}}$ percentile, rather than the segment average. It is important to note that upsampling from segment resolution to pixel resolution is needed. One could simply interpolate to a higher resolution, but we found it useful to make use of the inter-segment cross-talk to compute the final per-pixel boosting value. Let $\bar{v}_j$ be the average headroom of the $j^{\text{th}}$ segment, then the per-pixel gain is defined as:

$$\tilde{g}_i = \sum_{j=0}^{N-1} \bar{v}_j h_{i,j} \, . \tag{8}$$

The resulting front-of-screen gain may differ from this, as the corresponding pixel may be black or subject to clipping.

## Results

The method of boosting the backlight intensity, described by Eq. (4), has been applied to the image of Figure 1(a). The boosted backlight fields are shown in Figure 4(h), 4(i), and 4(j). Note how the boosted backlight appears brighter. Also the dark regions have remained dark, which is meant to ensure the black-level reduction known from local dimming. The tone mapping of the input has been based on the average headroom. This leads to the result shown in Figure 4(k) (cf. Figure 4(g)). Do note that the display system will indeed consume more power, but it does not contain more installed light than the reference system. The luminance gain has been quantified and can be seen in Figure 7.

To evaluate the method we provide two more images processed, fully automatically, with the same parameters as the first image. The output of the reference system, the tone-mapped output of the proposed system, and the corresponding gain is shown in Figure 8. Notice the large gain in the sky and the sea of Figure 8(b) compared to Figure 8(a). In these regions which are dominantly white-blue considerable levels of luminance increase of up to a factor 2.4 has been achieved for large parts of the image. Also note that the spatially varying tone-mapping does not create visible annoying artefacts for this particular image.

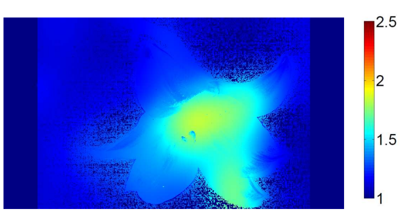


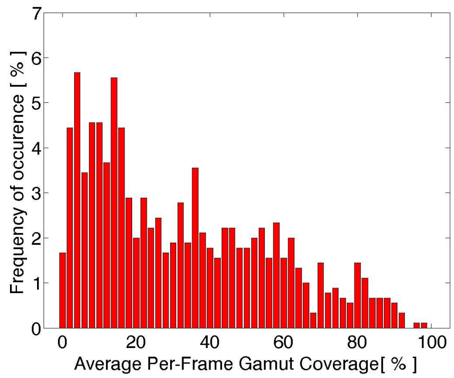

***Figure 7.*** *Per-pixel luminance boost comparing the reference system, Figure 4(g), with the boosted output, Figure 4(k).*

For the image of Figure 8(d), the tone-mapped output generally appears brighter. However, the discrepancy between the luminance increase of the edges and the centre region of the sun is visually annoying. In Figure 8(f), it can be seen that the centre region is not boosted at all, while the edges are boosted with close to 70%. The cause of problem lies in the local gamut. The local primaries in the sky and sun are rather constant. However, the luminance headroom is strongly dependent on the target chromaticity. For the red-yellow sky, two (or more) fields can be used to form a pixel of correct chromaticity, while the chromaticity of the sun can only be reproduced using a single field which limits the possibility of boosting luminance significantly.

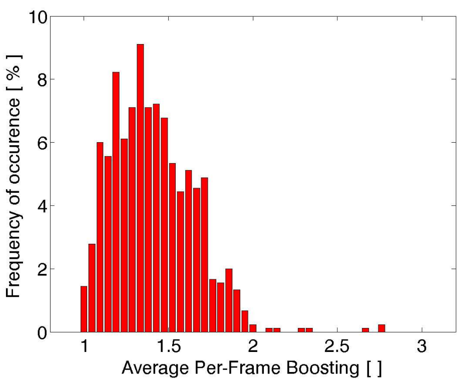
### *How Often Is Boosting Possible?*

The theoretical headroom varies between 1 and 3. In the examples above, the actual level of gain varies between 1 and 2, sometimes a little higher. In order to understand how often boosting will be possible and how much boosting is possible, we conducted a small statistical experiment. The starting point of the experiment is a video data set collected for IEC 62087 [9] and originally intended to investigate the power consumption of domestic video equipment.

It is worthwhile noting that while the content is rather desaturated, this does not need to be an advantage for the method. Extremely saturated content, like animations or computer programs like text editors, can also form good boosting candidates. The experiment was carried out as follows: 1) each frame was divided into 12 by 20 segments; 2) local primary desaturation was applied; 3) the backlight was boosted for bright segments; and 4) the average per-pixel headroom and the gamut coverage in CIE 1976 $u'v'$ was recorded.




(a)




(b)

***Figure 9.*** *Results from the statistical experiment on the IEC 62087 video sequence [9]. (a) The frequency of occurrence of frame-average gamut coverage expressed in CIE 1976 $u'v'$. (b) Frame-average luminance headroom frequency of occurrence.*

The collected statistics can be used to understand the gamut coverage of the local primaries. As can be seen in Figure 5(e), one can expect the largest headroom for the smallest local gamut. It is therefore interesting to understand how often the local primaries will span a small gamut. We have plotted the histogram of the average gamut coverage per frame in Figure 9(a). The average gamut coverage is 33% and the 90$^{th}$ percentile is 68%. These results indicate that even with a modest segmentation of 240 segments, the resulting local gamuts are considerably smaller compared to the reference gamut.

A reduced gamut potentially allows luminance boosting, but as illustrated in Figure 5(e) this depends on the chromaticity coordinates of the pixels in question. In Figure 9(b) we show the histogram of the average headroom/boosting per frame. The average headroom is 1.43 and it can be observed that headroom up to a factor of 1.7 is frequently occurring. Notably is also that headroom above 2.0 does not occur frequently.

## Discussion

The existing scheme for local primary desaturation, which consists in maximum reduction of the gamut coverage, may not be the best approach to boost luminance. In order to maximise luminance boosting, two or more fields must be used to create the desired chromaticity. New schemes for local primary desaturation should therefore maximise LC-panel drive levels of all fields while simultaneously reducing gamut coverage. This offers an interesting trade-off between high-brightness and colour breakup artefacts. As annoyances of colour breakup are most frequent in large uniform regions and high contrast regions, one could switch between approaches for luminance increase and colour breakup reduction, by analysing the video content.

Images with boosted luminance created by the proposed method can lead to convincing results, however, in some situations, the results are not preferred over the non-boosted images. This is most notably when a white region is boosted significantly less than a nearby saturated region. This situation corresponds to rendering with a white point of low relative brightness. We propose to reduce luminance (by means of the LC-panel) in the saturated regions when this occurs.

## Conclusions

In this paper, we have introduced the concept of luminance boosting for a colour-sequential display. The theoretical maximum luminance increase is 300% without additionally installed light. As the display system reproduces colour without the use of colour filters, it is considerably more efficient than the ubiquitous colour-filter-based LCD.

A method to increase the luminance in bright regions while maintaining the low black level in dark regions were proposed. Additionally, two approached to tone mapping subject to the constraints of the local gamut headroom was proposed.

It was determined that an average of 143% boosting could be expected for regular video content, and that more than 200% boosting does not occur frequently. For other image content such as text editors or animated movies the boosting could be considerably higher.

## References

[1] H. Seetzen, *et al.*, High dynamic range display systems, Proc. ACM SIGGRAPH 2004, 760-768, (2004).

[2] F.-C. Lin, Y Zhang, and E.H.A. Langendijk, Color breakup suppression by local primary desaturation in field-sequential color LCDs, IEEE J. of Disp. Tech., 7(2):55–61, (2011).

[3] Y. Zhang, F.-C. Lin, and E.H.A. Langendijk, A field-sequential-color display with a local-primary-desaturation backlight scheme, J. of the SID, 19(3):242–248, (2011).

[4] H. Hasebe and S. Kobayashi, A full-color field sequential LCD using modulated backlight, Proc SID, 16:81–83, (1985).

[5] F. Yamada, H. Nakamura, Y. Sakaguchi, Y. Taira, Sequential-color LCD based on OCB with an LED backlight, J. of the SID, 10(1):81–85, (2002).

[6] E.H.A. Langendijk, A comparison of three different field sequential color displays, Proc. Int. Disp. Workshops, 12(2):1809–1812, (2005).

[7] Y. Zhang, E.H.A. Langendijk, M. Hammer, F.-C. Lin, A 120 Hz spatio-temporal color display without color breakup. Proc. SID, (2011).

[8] Y. Zhang, E.H.A. Langendijk, M. Hammer, and F.-C. Lin, A Hybrid Spatial-Temporal Color Display With Local-Primary-Desaturation Backlight Scheme, IEEE J. of Disp. Tech., 5(12):665–673, (2011).

[9] International Electrotechnical Commission. IEC 62087 (100/1331/CDV), methods of measurement for the power consumption of audio, video and related equipment, (2008).