High Quality LCD Imaging System - Beyond 8 Bits -

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Abstract

It was pointed out a couple of years ago that R:G:B=10:12:9 bits in tone scale resolution is required to achieve reality-reproduction by a display. In connection with the report, we have explored a visibility of contour artifact in high quality TFT-LCD with a resolution of R:G:B=10:10:10 bits. In our experiment, the 10 bits system had good ability in tone scale reproduction and invisibility of contour artifacts was improved significantly. We considered the results of the experiment in conjunction with properties of the human visual system, since the visibility of the contour artifact must relates to them, such as spatial frequency response, contrast sensitivity property and light adaptation property. Also we pointed out some issues to be considered towards high quality LCD, such as an issue of qualitative evaluation and color management.

Introduction

The picture quality of LCD has been analyzed from various points of view.[1,2] Figure 1 shows an example of the picture quality of LCD display.[3] As is common, the present LCD was compared with CRT. According to the result, LCD has already reached the level of picture quality corresponding to CRT except for problems relating to motion picture such as motion blur and color management.

On the other hand, for the purpose of configuring an imaging system capable of expressing the emotion, Prof. Miyahara has investigated a required performance of the imaging system by means of subjective evaluation.[4] Though their research was aimed at how the display should be in order to express the sensation of shadow or depth of the picture, and not on common terms of evaluation shown in Figure 1, it suggests a future direction of technical improvement of displays that have already achieved a certain level of picture quality in conventional evaluation terms.

In their experiments, Prof. Miyahara has pointed out that the present areas where the LCD lacks substantially are especially the contrast ratio and tone scale reproduction.

Among them, in this study, we investigated on improvement of the tone scale reproduction as for further enhancement of the LCD picture quality.

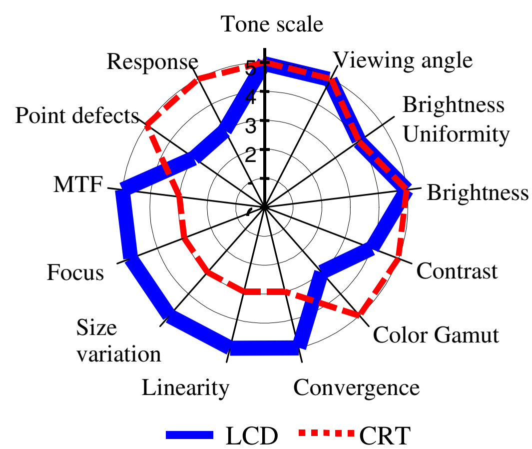

Figure 1. Comparison of picture quality of displays

Preliminary Experiment – Problems of Conventional 8 Bit System –

The previous work of Prof. Miyahara required a bit depth of R:G:B=10:12:9 bits to keep the color difference of quantization error below a detectable limit under γ = 3.0 condition.[4] On the other hand, since the maximum bit depth of the ordinary LCD is, as widely known, R:G:B=8:8:8 bits, we first initiated a subjective evaluation to confirm how much the contour artifacts would actually be visible as a result of 8 bits quantization.

The experimental conditions are detailed in Figure 2. A high-resolution LCD of R:G:B = 8:8:8 bits was set under an adjustable lighting system. As shown in Figure 3 and Table 1, we prepared seven kinds of ramp test images for each primary color with different slope and brightness and evaluated the visibility of contour artifacts under three different illuminating conditions. To be free from any undesired noise effect, the DVI digital interface was used as an interface between the PC and LCD.

Based on the five-grade impairment scale, the mean opinion score (MOS) for the subjects was given as the results of two observers.

5:imperceptible, 4:perceptible, but not annoying,
3:slightly annoying, 2:annoying, 1:very annoying

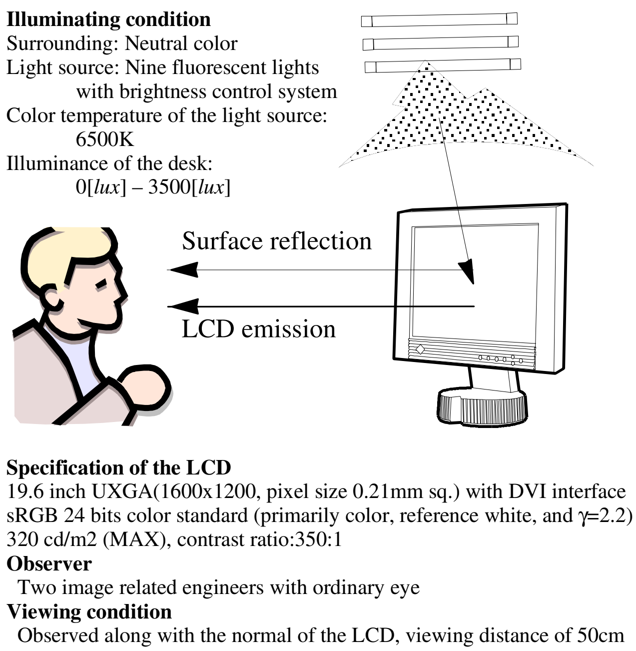

Figure 2. Configuration of the evaluation

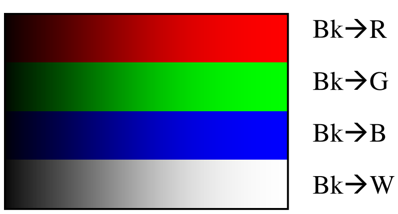

Figure 3. Test charts used

Table 1. Specification of the Ramp

Chart No.	Left	Center	Right	Spatial freq. of the bar(cpd)
1	0	127	255	11.2
2	0	31	63	3.2
3	64	95	127	3.2
4	128	159	191	3.2
5	192	223	255	3.2
6	32	39	47	0.8
7	48	55	63	0.8

Figure 4 shows an experimental result of the mean value of two observers' MOS. Depending upon the lighting condition and test chart used, the false contours of the LCD of R:G:B=8:8:8 bits was clearly visible.

In summary, the visibility of the contour artifacts caused by quantization were:

(1) Depending upon the slope of the grating, the visibility of the false contour varies a lot. Having a steep slope such as in Chart 1, no contour artifact was visible.

(2) False contours were likely to be visible in the area of as low brightness as 32 to 64/255 such as Charts 2, 6 and 7. For evaluation in a darkroom, more distinct false contours were perceived.

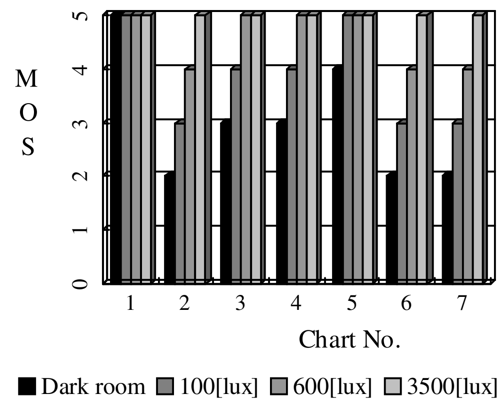

Figure 4. Results of the preliminary experiments

Consideration of Results of the Preliminary Experiment

The above-mentioned (1) and (2) can be better understood if they are interpreted in relation to the property of the Human Visual System(HVS).

First, why the visibility of the contour varies strongly depending upon the slope of the gratings can be understood if it is considered in relation to a spatial frequency response of the HVS as shown in Figure 5[5)] as an example.

Shown in the Table 1 were spatial frequencies of the bars that performed each gray value under the observed conditions of the experiment. It is obvious that spatial frequencies of the bars depend on the slope.

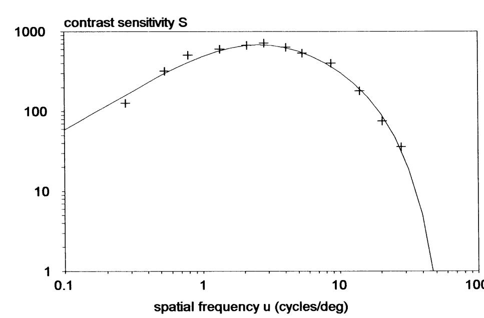

Figure 5. Property of Human Visual System[5]

When comparing the special frequency shown in Table 1 to spatial frequency response shown in figure 5, spatial frequency of the bars in which false contours were visible are nearly equal to those of highly sensitive portion in HVS. Although the figure 5 is for a “just noticeable difference”, visibility of the contour artifact should relate to slope and special frequency response of the HVS.

Next, an experimental result that false contours were more visible in the area of as low brightness and especially in a darkroom are considered to relate to the contrast sensitivity property[6] and adaptation property[7] of the HVS.

Figure 6 shows an example of the contrast sensitivity property of the HVS. The experiment in the Figure 6 is for a visible threshold value of ΔB, under the condition that brightness of background is B_0 while the central zone is B and B plus ΔB. In the experiment, a relative discrimination threshold zone ΔB/B becomes the smallest when B_0 is equal to B. When there exists a difference between B_0 and B, the discrimination threshold goes larger. In other words, the sensitivity deteriorates. The discrimination ability decreases when there exists a difference between brightness of display’s background (i.e. room illumination) and those of the display.

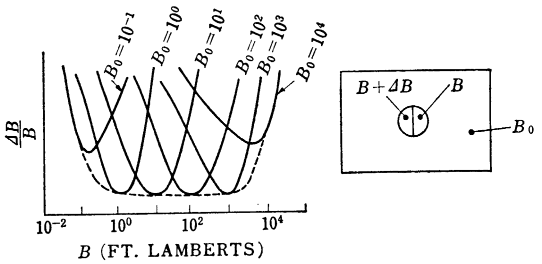

Figure 6. Contrast Sensitivity property of human visual system[6]

Under an ambient light condition, the different of the brightness goes large, and clipping of the dark part of the screen by surface reflection light may occur. In addition, overall sensitivity of the HVS deteriorates because of the adaptation. Due to the reasons above, slight differences in bright portion were not perceived under the ambient light condition.

On the other hand, in a darkroom, HVS becomes darkness-adapted and increases in sensibility as a whole. In addition, in low-key portion like 32 to 64/255, a difference in brightness decreases when compared with the background, and thus the ability of brightness discrimination is increasing. In addition, there were no reflection in darkroom, a picture is reproduced precisely even in the dark portion. Those were the reasons why contour artifacts were perceptible especially in a darkroom.

Summary of the Preliminary Experiment

Throughout the preliminary experiment, we found that a picture with gentle slope in the brightness around 32 to 64/255 was a “killer image” from a standpoint of the visibility of the contour artifacts of 8 bits system. Therefore, we should make further improvement of the bit depth at least for mitigation of the problem.

For reference in the experiment, we evaluated some pictures of high-quality natural photographs that were taken by a high-quality digital camera with a built-in 14 bits A to D converter, and computer graphics (CG) images. As a result, we confirmed that the invisibility of false contours as expected from common usage had largely relied on the SN ratio of an image. For example, the problem was hardly worrisome with the photograph taken with the digital camera, but was very worrisome in CG.

High Bit Depth Technology for LCD

Following the preliminary experiment, we configured a high bit depth LCD to evaluate how we could reduce the visibility of the contour artifact by improving the bit depth of the LCD. We worked out a higher bit depth LCD of more than 8 bits combined with digital halftoning technology.[8] since various digital halftoning technologies may possibly be utilized for LCD and its technical verification is comparatively easy.

Of the digital halftoning technologies, dithering methods, error diffusion, and frame reversing control (FRC) have been well known. All these technologies are basically block based processing technology that forms by the unit of several pixels or several frames. This means that the technology controls the bit depth within the block, thus achieving high bit depth in tradeoff for its resolution and/or temporal domain properties.

Meanwhile, there is the fundamental technology for the LCD that relates to the driving, so-called the AC driven method.[9] The technology is to be used for the purpose of protecting liquid crystal from being permanently destroyed as a result of the direct current application. It serves to reverse the polarity of driving voltage per frame, scanning line and/or pixel. The alternation makes the driving signals like AC, that is why it is called the AC driven method.

Thus, the AC driven technology is an indispensable technology for the LCD. However, if above-mentioned digital halftoning technology is applied for the LCD, it may have interference between the unit of alternating current operation and that of the resolution or time property to be traded off by the bit depth expanding technology. The interference causes not only the deterioration of the picture quality, but freezes the picture up in the worst case due to application of direct current to the LCD. Therefore, a sufficient consideration will be necessary before the digital halftoning technology is applied for the LCD.

On the other hand, there is the Robert’s Noise Modulation Technology[10] which is compatible with AC driven method of the LCD. Being one of the traditional image coding technologies, the Robert’s Noise technology was to add noises to signals before quantization in order to decrease visibility of quantization errors. It then subtracted the noise at the receiver, but in application for displays by Lippel,[11] the noise is not removed. Figure 7 shows an example of its basic configuration. This technology can be interpreted as a kind of digital halftoning technologies using amplitude dither rather than spatial dither so that there is no spatial resolution loss. If the technology is applied to the LCD, it is expected to cause little perceived effect on the AC driven technology due to none of specific processing block available.

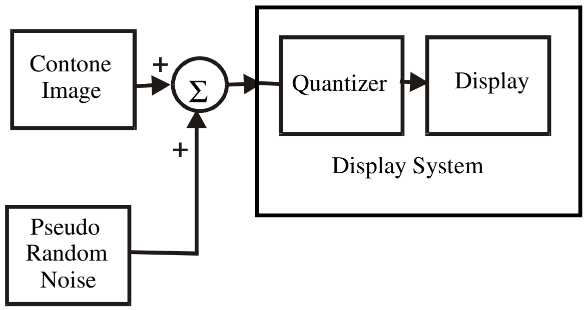

Figure 7. Basic application of Robert's noise modulation to displays

Prototype Display System

For a system with R:G:B=10:10:10 bits as a target, we configured a prototype of high bit depth LCD display system with application of the Robert's technology. The schematic diagram is shown in the Figure 8. The system consisted of 20.1 inch UXGA LCD, Windows PC and a newly developed display card that was built into the PC.

The display card was connected to the main body of the PC via PCI bus and therefore was capable of high-speed data transmission. Pictures at the PC were formatted in RAW data at R:G:B=16:16:16 bits. The card contained the digital halftoning processing in which R:G:B=10:10:10 bits signal are condensed into R:G:B=8:8:8 bits as output signals via DVI digital interface of R:G:B=8:8:8 bits specifications.

The LCD, that is considered as the high-end up to the present, was used as a display device having R:G:B=8:8:8 bits in the UXGA format. Combining with the display card above, pseudo-conversion to 10 bits took place, working as a beyond 8 bits LCD system.

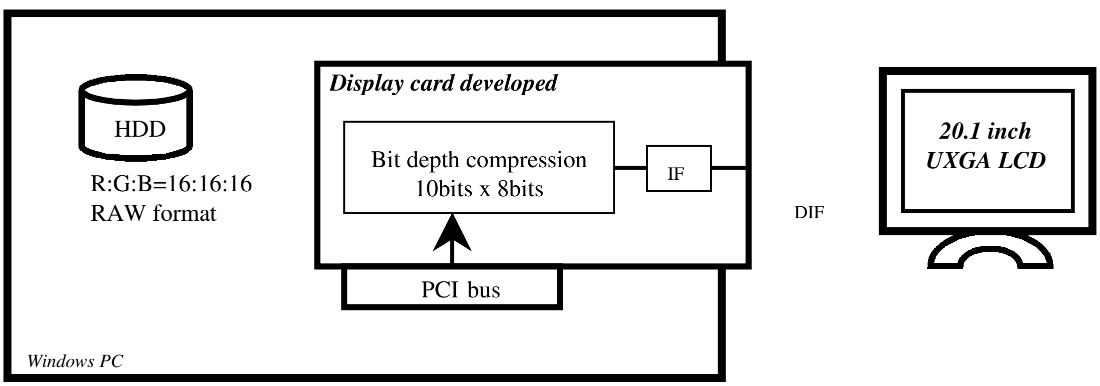

Figure 8. Schematic diagram of the high bits depth LCD imaging system

When the halftoning technology is applied to heighten bit depth, like this trial, deterioration in SN ratio as well as in resolution remains to be considered as an issue. Thus, two subjective evaluation were confirmed in advance,

(1) Evaluation on the visibility of the noises in comparison with the visibility of the false contours as we can confirm with charts 6 and 7 (correspond to one quantized step).
(2) Subjective evaluation of the reproduction of the patterns that cannot be presented in 8 bits systems like +/-1 to 2/1024 in its amplitude.

Although we do not describe those evaluations in detail here, we encountered no visible noises and came to the conclusion that even the patterns that were impossible to handle in 8 bits systems were reproducible in a good condition.

As shown in above, we did not find any visible problems such as deterioration in the SN ratio and decline in resolution, except the merit of the false contour decrease on a flat surface. We also found it possible to further extend into higher bits.

Picture Quality Evaluation

First, using ramp images as shown in Figure 3, we made a comparison in the visibility of false contours same as in the preliminary experiment. Signal values were all quadrupled to conform to 10 bits. All the spatial frequencies of the bars shown in Table 1 should be multiplied by four for 10 bits system.

The result is shown in Figure 9. When compared with the visibility of false contours shown in Figure 4, an evaluation score marked an increase significantly under any evaluation condition and with any chart, which showed a drastic decrease in the visibility of false contours.

With charts 6 and 7, on the other hand, false contours were perceived a little. They had the same spatial frequencies of the bars as chart 2 in the preliminary experiment and corresponded to one quarter of the brightness difference. In other words, it showed an extremely gentle slope with one quarter of what we had in the preliminary experiment. In such a case, a perceptible false contour still remained even in the 10 bits system.

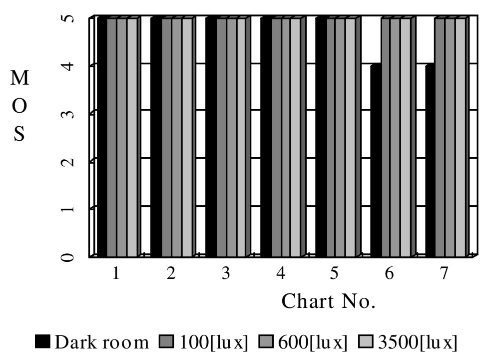

Figure 9. Experimental results

Same as in the preliminary experiment, we also made an evaluation test of high-quality natural photographs, along with CG pictures, taken by a high-quality digital camera with a built-in 14 bits A/D converter. The result was that a false contour had been slightly perceived on CG pictures, same as in the case of evaluation by ramp images, while any false contour was not perceived at all in the pictures taken by the digital camera. The above confirmed a significant effect of 10 bits system for representation of a low-contrast surface with a high SN ratio in particular.

Considerations

In this paper, we focused on the visibility of false contours, and we made a subjective evaluation of display. Through the experiments, we found it necessary to investigate what attributes should be evaluated and what method to be taken up in the future high quality display.

How to Make Quantitative Evaluation of Beyond 8 System

First, we suspect if the current determination method of the bit depth in ordinary specification sheet is proper method for high quality system.

Currently, the bit depth resolution is determined as a resolution of the bit depth regarding one pixel. However, it is quite difficult to visually detect any quantization error only within one pixel of several hundred microns square, even though the bit depth resolution by the unit of each pixel would be electrically definable. Needless to say, the measurement would be difficult, too. In order to represent the tone scale, a proper size of area up to several hundreds pixels is required. The conventional method of defining bit depth resolution by the unit of pixels means nothing but an oversimplified discussion on the numerals that cannot be visually and optically guaranteed.

Then, suppose subjective evaluation of the visibility of the false contour is only way to evaluate the bit depth, some new definition on an evaluation environment and spatial frequencies of evaluation patterns will be required. In our experiment, we found that the visibility of contour artifacts is depended upon evaluation environment and spatial frequencies. Those two factors are closely related to each other. Discussion of spatial frequencies is related to that of the above-mentioned “size of the area” to be measured quantitatively, while discussion on evaluation environment is related to the way of quantitative evaluation.

For example, the color notation by mean of L*a*b* suggests the necessity to consider the effect of adaptation property of the HVS according to evaluation environment of the display. According to the definition of the L*a*b*, its value is normalized by reference white as a standard. It is considered that the L*a*b* is a kind of a method that puts a von Kries-type adaptation property of the HVS[12] into XYZ.

However, when a display color is calculated in accordance with L*a*b*, in many cases, we do not consider the adaptation state of the HVS. In other words, in spite of not having a standard color of 100% pure white exist within the display area of a particular picture, 100% standard white color is still employed as a standard for normalization of the calculation of L*a*b* color value.

The above disagreement becomes obvious when we intends to prove the result of subjective evaluation comparing two dark pictures by means of L*a*b* color difference. Obviously, L*a*b* value calculated based on the 100% white as the standard for a dark picture is naturally in smaller. Therefore, color difference might be negligible in many cases. Nevertheless, when actually observed, we can still recognize a difference surprisingly well.

In this case, if the value relevant to the dark screen, that should be a standard of adaptation of HVS, is substituted as a normalized coefficient of the L*a*b*, the color difference value required in calculation becomes large, and must be in agreement with color difference felt in the state where it is actually observing. It may easily be explained by considering that HVS does not adapt to 100% white in this case, but to average of the two dark pictures.[13] Since it has been accepted that the HVS will be adapted to average conditions of display,[14] how to select a standard white color, therefore, remains as a problem for the future when the conventional color notation system of L*a*b* would be used as a quantitative evaluation of quantization error.

Meanwhile, perception of color difference varies not only in accordance with adaptation conditions of the HVS but in relation to targeted spatial frequencies. In order to realize the system that can be displayed without disturbance of all the input signals, system design that takes these things into consideration at least must be required.

Color Management Issues of the High Quality LCD

As mentioned earlier, color management should be a problem in future high quality LCD. From the viewpoint of the ICC color management, the additivity and the proportionality are the basic requirements for the display. However, from the consideration of the LCD components, LCD does not satisfy these requirements. Figure 10 shows an example of the retardation of the liquid crystal that causes a physical displacement of the primary colors of the LCD as shown in Figure 11. Also Figure 12 shows an example of the cross-talk between channels that causes a lack of the additivity.

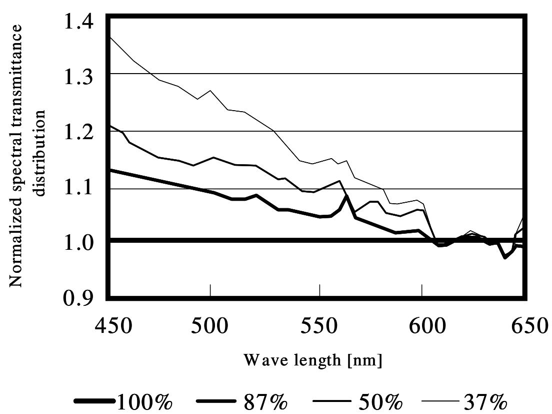

Figure 10. Normalized spectral transmittance distribution of the LC panel corresponds to digital code value.

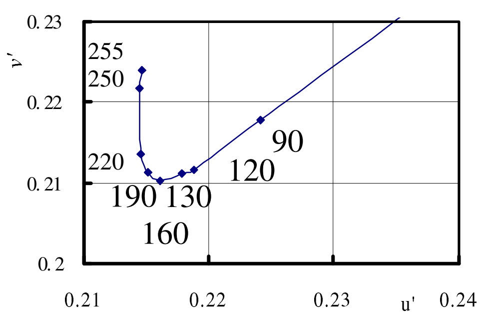

Figure 11. An example of the variation of the color coordinates of the blue primary. Numbers correspond to the CV.

In order to achieve a good color management of the LCD that lacks basic requirements of the ICC shown in Figure 11 and 12, some statistical approach such as high-order matrix color compensation method would be necessary. In this experiment, we used a 16 bits system in the calculation of 3x8 matrix color compensation for the 10 bits LCD. Shown in Figure 13 is an example of a result. Significant improvement of the color management was achieved by means of 10 bits LCD as well as a calculation in high accuracy.

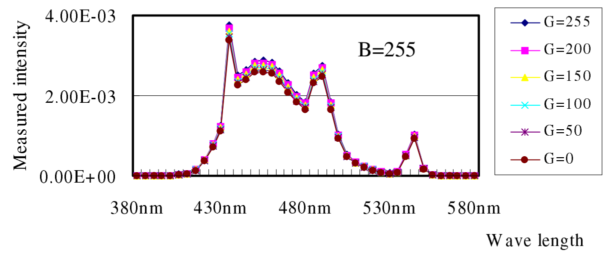

Figure 12. An example of the cross-talk from Green to Blue.

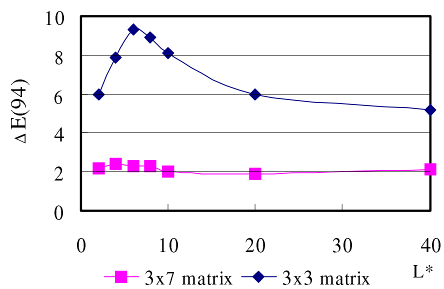

Figure 13. Measured results of the precise color management

Conclusion

A high bit depth display system, which is a direction of the future display devices, has been configured and evaluated. In this study, we focused on the visibility of the contour artifacts of the LCD.

As a result, false contours were clearly perceived in some pictures having R:G:B=8:8:8 bits. Through the experiments, we confirmed the limit of the picture quality of the 8 bits system. On the other hand, a drastic improvement in false contour has been achieved in 10 bits system while no deterioration in the SN ratio was observed in the prototype system.

Throughout the whole experiment, the picture quality was drastically improved if the display system is improved to 10 bits. For representation of natural pictures taken by camera, the 8 bits system gave some perceptible false contours while the 10 bits system succeeded in improving the picture quality. For evaluation by chart and with CG pictures, on the other hand, we still recognized an existence of killer image in the 10 bits system.

Based on the evaluation results, some issues on quantitative evaluation of the L*a*b* color difference, and color management issues were also considered.

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Biography

Mr. Yasuhiro Yoshida is a research scientist of the IC group in Sharp Corporation. He has been with Sharp since 1986 and working for over 10 years in color science. His current responsibility at Sharp is to improve the picture quality of the LCD's. Mr.Yoshida received his MS degree in Color Imaging. He is a member of the IEICE (Institute of Electronics, Information and Communication Engineers of Japan), SMPTE and IS&T.