P-75: *Late-News Poster:* Metrology Issues for LCD-TVs

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Abstract

This paper introduces a novel compact approach to measurement and characterization of the visual performance of LCD-screens when ***high visual fidelity*** of the displayed images is a prime issue. We present instrumentation, procedures and evaluations for assessment of the visual properties of LCD-TV screens with minimum efforts as a basis for a clear and objective rating of their performance. Measurement and evaluation of color and gray-scale fidelity across the viewing-cone and under ambient illumination are the main topics of this paper. Typical results for a high-quality LCD-monitor are presented. A novel concept for scanning of the viewing-directions with simultaneous acquisition of 9 spectra at 9 angles of inclination is introduced.

1 Introduction

LCD-monitors have been successful in replacing CRT-monitors for office work over the last years. The next challenge for LCD-screens is the market for TV and video applications. The essential difference between these two application classes lies in the image contents that are presented to the observer [1]:

- in office work, most of the (quasi-static) image content does not have any original existing in the real world (e.g. alpha-numeric characters, letters, numbers, signs, etc. and other abstract symbols like line graphics). The objective is fast and secure recognition and interpretation of the presented abstract visual information over long periods without negative side-effects (ergonomic safety).
- in TV and video-applications most of the image content is captured from objects and scenes that do have originals in the real world (e.g. landscapes with sky and pastures, human faces and skin, etc.) and here the match between the real scene or object and the one presented on the screen is the key objective, i.e. the *fidelity of the representation*.

While the range between the extremes of *reality imaging* and *virtuality display* is increasingly bridged by *mixed realities* (i.e. *augmented reality* and *virtuality*, see [2]), there is a pronounced tendency in computing and telecommunications for convergence of both applications and thus the increasing demand for *high-fidelity* display devices that cover both application classes.

The *visual fidelity* of TV and video-images is not only determined by the display device, it also depends on the ambient conditions under which the images are observed (*surround*) and on the state of adaptation of the human observer. This complex subject is addressed by *CIE color appearance models* (e.g. CIECAM97s - [3]) and it is outside the scope of this paper. We restrict ourselves to the measurement of physical quantities that form the basis for objective rating of the visual performance of LCD-TV-screens. Limiting values that define the borders between acceptable and not acceptable visual performance for a specific application shall then be distilled from adequate ergonomic experiments.

The characterization process and the resulting characteristics describing the visual performance of LCD-screens must be clear, transparent and understandable. The resulting *figures of merit* should not fool the user (compare the misused concept of the "viewing angle/angel") but provide clear information about the visual performance of the display in the specific application (here TV and video) that can be used as an objective basis for product comparison and purchasing decisions also by laypersons.

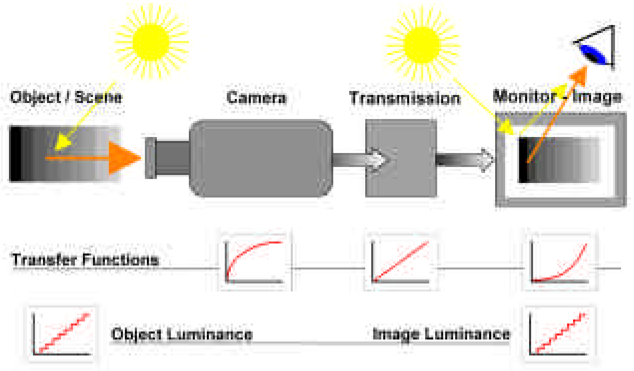


Figure 1: Television/Video transmission chain from object/scene to the presentation on an electronic visual display-screen with indication of the transfer functions of the individual components.

The functional objective from the users perspective is simple: the display shall provide a high contrast with "vivid natural" colors (*high visual fidelity*), no changes shall be visible with viewing-direction (CRT-like) and no artefacts shall be obvious (e.g. false contours), especially in the case of moving images.

2 Items to be evaluated and rated

The metrology for LCD-screens as presented here is focused on their known weak-spots: the variation of all optical quantities with viewing-direction and the limited dynamic capabilities (i.e. slow response times, hold-type display) of nematic LCDs.

The *visual sensation* of an observer (represented here by the CIE 1931 standard colorimetric 2°-observer) watching images on electronic displays is depending on:

- stimulation of the display (electrical data-input = image contents),
- viewing-direction and location of the observed spot/area on the display (both coupled to each other),
- time (temporal effects ranging from ms to hours),
- ambient conditions (illuminations situation -> reflections, state of adaptation of observer) and climatic conditions (e.g. temperature).

The visual information on the display screen becomes a linear function of the tristimulus values of the object/scene only when the *electro-optical transfer functions* (EOTFs) of the display are the exact inverse of the camera transfer-function (see fig. 1). This condition must be fulfilled for all viewing-directions and under ambient illumination to ensure *visual fidelity*.

3 Electro-optical transfer functions

The relation between the electrical input signals of an LCD-screen and the displayed visual information is described by the *electro-optical transfer function* (EOTF) for each primary color of the display. The EOTFs relate tristimulus values X, Y and Z (with Y ~ luminance) of the displayed information to the electrical input signals as follows (without bias):

$$\text{EOTF} = X_0 \cdot (r, g, b)^{\gamma} \qquad (1)$$

with X_0 = Maximum of tristimulus values X, Y and Z

r, g, b normalized input values for R, G and B

γ exponent ("gamma value").

For *chromatic fidelity* (i.e. the tristimulus values of the displayed colors are linear functions of the tristimulus values of the objects and scenes), the ***additivity of the primary colors*** of the display must be assured. Additionally, the ratio of the EOTFs of the primary colors, effecting the white-balancing, must remain the same at each driving level and viewing-direction to assure a stable chromaticity of the displayed image content. The maximum luminance should remain constant to avoid dark images at oblique viewing directions.

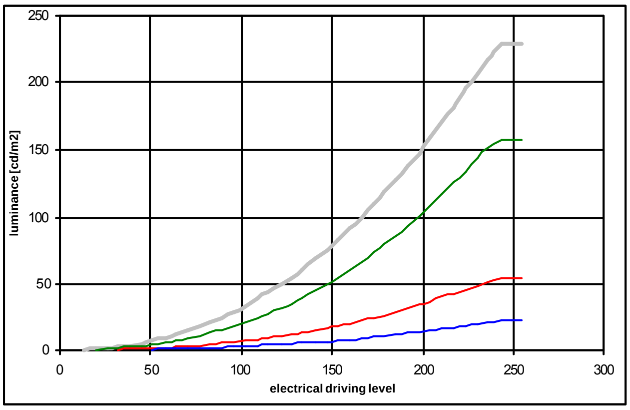


Figure 2: EOTFs (Y) of an LCD monitor versus electrical driving for normal viewing-direction under darkroom conditions. Primary colors R, G and B and the achromatic state.

3.1 EOTF artefacts

The EOTFs of fig. 2 show 2 artefacts: the curves saturate for input signals above 240 and there is a non-zero dark state of about 0.6 cd/m^2 caused by the non-zero transmission of the LCD.

Spectra and thus the chromaticity of the displayed images may be negatively affected by:

- inaccuracies of transformation from RGB input signals to actual LCD data-voltages (via insufficient LUTs and computations) causing a misbalance between the primaries,
- variation of spectral transmittance of LC-layer with driving voltage (state of deformation of LC, dispersion of refractive indices).

The additivity of the primaries can furthermore be negatively affected by two kinds of crosstalk [4]:

- optical crosstalk due to non-ideal separation of primaries,
- electrical crosstalk due to capacitive coupling.

A necessary condition for the EOTF fidelity is that each curve and its first derivative must be increasing in a monotonous way with the input signal, thus, the second derivative must be positive for all driving levels and all viewing-directions. Since the numerical value of TV-gamma is specific for each region on earth, its value has to be evaluated with a model e.g. according to eqn.1 (non-zero luminance, L_0, of dark-state (r=g=b=0) according to the recommendations of the ITU [5]). A thorough discussion of the various models for the EOTF (e.g. GOG, GOGO, etc.) is given by Deguchi, et. al. [6].

$$\text{EOTF} = L(d) = c \cdot L_{max} \cdot d^{\gamma} + L_0 \qquad (2)$$

The luminance of the bright-state usually decreases with angle of inclination and thus L_{max} decreases with viewing-direction.

3.2 Additivity of primaries

The EOTFs of the three primary color channels must be well synchronized in order to assure additivity and thus stable colors and achromatic display states that do not show chromatic changes with driving. In addition the synchronization of the three EOTFs must be independent of viewing-direction in order to maintain the chromaticity of chromatic and achromatic states and thus *the chromatic fidelity*.

L (white = R+G+B) = r L(r) + g* L(g) + b* L(b)*

with r*, g*, b* = coefficients for balancing of the white-state

Based on the requirement of RGB-additivity we can evaluate the chromatic fidelity of LCD-screens with respect to electrical driving and viewing-direction by analysis of the gray-states only. The "shape" of the EOTFs (i.e. the match to a power function) is obtained by evaluation of the *luminance* of the gray-states versus electrical driving (at the design or the normal viewing-direction, DVD/NVD, respectively, and under darkroom conditions). The stability of the individual EOTFs with respect to viewing-direction is evaluated via measurement of the tristimulus values of a sufficient number of gray-states at different viewing-directions.

4 Effect of viewing-direction

Each point on a display is seen from a different direction, thus all variations of visual quantities with direction must be sufficiently small for constancy of chromaticity across the display area and for observers that are moving around in front of the TV-screen.

In the case of LCD-TVs the *viewing-cone* is the range of viewing-directions with unnoticeable or acceptable visual degradations (e.g. decrease of luminance and contrast, change of chromaticities, etc.). While users and observers of computer monitors keep quite fixed positions with respect to the display this is not the case for TV-applications. As a consequence one may wish the viewing-cone of a TV-display to cover the entire hemisphere in front of the screen (θ_{max} = 90°) as it is (theoretically) the case with CRTs. The geometrical distortions resulting from oblique observation (foreshortening, reduction of 29% at θ = 45°) are annoying in work-situations but probably acceptable for entertainment.

The *viewing-cone for TV-applications* should be specified by the limiting values for variations of luminance, contrast or chromaticity versus angle of inclination, θ_{limit}, for a minimum of 8 azimuth-angles (**0°**, 45°, **90°**, 135°, **180°**, 225°, **270°**, 315°) to include the diagonal planes. Within this viewing-cone, luminance and contrast shall not drop below the chosen limiting value and the variation of chromaticity shall be below the specified limit (e.g. $\Delta u'v' < 0{,}02$ for $\theta_{max} = 45°$, compare Nakamura [7]).

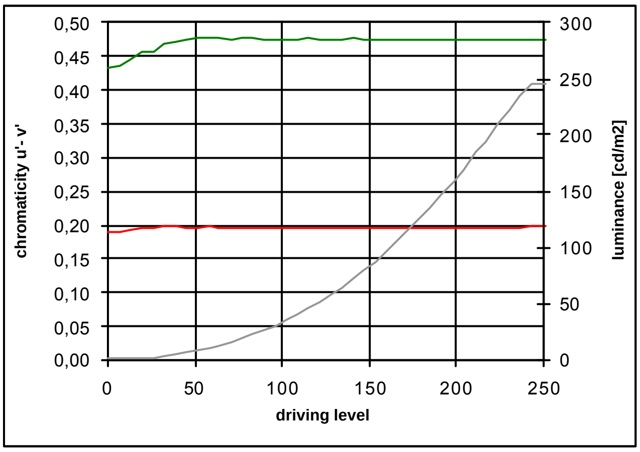


Figure 3: EOTF (Y) and chromaticity of an LCD monitor versus electrical driving for normal viewing-direction under darkroom conditions, $\Delta u_{max}' = 0{,}0089$, $\Delta v_{max}' = 0{,}0414$.

For the individual experience of *visual fidelity* it seems as well important that the visual properties remain sufficiently constant for each observer within the individual field-of-view (area of display) and viewing-cone. On the other hand, typical colors, e.g. those of skin tones, shall remain the same no matter from which direction they are seen and experiencing a noticeable change of chromaticity when moving along the TV-screen seems not acceptable. This requires low directional gradients of chromaticity for any viewing-direction within the usable viewing-cone.

The variation of chromaticity of two achromatic states (full-white and 50% gray) is compared in table 1. The variations of the medium gray-level are more pronounced that that of the full-white state. The chromaticity variation becomes maximum in the black state of the display (well known for IPS-LCDs).

4.1 Specification of contrast

In data-sheets of LCD-monitors and of TV-sets numerically impressive *contrast* values can often be found. In order to make these "contrast-numbers" significant characteristics, the following conditions have to be known and specified:

- Electrical input (= test-pattern [gray-levels, full-black and white], full-screen , window, grille, etc....),
- Display control-settings (luminance, contrast, black-level, white-level (if available), white-chromaticity, gamma, etc.),
- Size and location of field of measurement, angular aperture of light-measuring device,
- Direction of observation or range of directions (VC),
- Ambient conditions (illuminance level, spectrum, [daylight, incandescent], geometry of illumination).

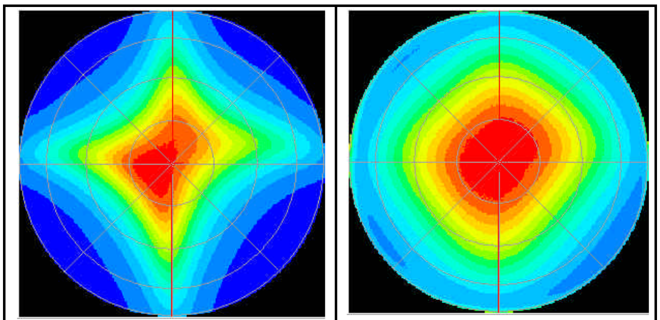
255	**@ normal**	**max**	**min**	**D**	**D-u'v'**
u'	0,1971	0,2059	0,1838	0,0221	**0,0365**
v'	0,4747	0,4897	0,4606	0,0291	
128					
u'	0,1953	0,2134	0,1783	0,0351	**0,0567**
v'	0,4752	0,4917	0,4472	0,0445	

Table 1: Variation of chromaticity of two achromatic states (R=G=B=255, 128) with viewing-direction for $\theta_{max} = 80°$ and for $\phi = 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°$. The variation of chromaticity with viewing-direction, $\Delta u'v'$, is larger for the 50% gray-level (128) than for the full-white state (255).

4.2 Effect of ambient illumination

Most of the impressive "contrast-numbers" available in data sheets are measured under *darkroom conditions* which do not correspond at all to the actual application situation. It would be more informative however to know the contrast under typical indoor illumination conditions for a well founded solid product comparison and a justified purchasing decision. This contrast can easily be evaluated for one viewing-direction (e.g. design viewing direction) according to the arrangements of ISO 13406-2 and ISO 9241-7 with a uniform conical 15° illumination source set to the specified direction of light incidence (as close as possible to the normal viewing direction). The luminance of this source produces an illuminance E_{amb} at the location of the measurement field that can be adjusted to realistic illuminance values (e.g. 300 lx = workplace situation, 50 lx = home-cinema). When this *contrast under ambient illumination* has to be measured as a function of the viewing-direction, either an isotropic hemispherical illumination has to be provided or the source of illumination has to be moved to the specular orientation for all viewing-directions during the measurement.

In order to evaluate the effect of a bright ambient lightsource on the contrast we have used the 15° source according to ISO 13406 at a luminance of 6,840 cd/m^2 in the specular 15° inclination setup in which the contrast was reduced to 1.9:1. The same bright white illumination (CCT of 6 500 K) reduces the saturation of the colors (bleaching) and the range of colors that can be displayed (color gamut) as shown in fig. 5.



Darkroom Contrast	Contrast @ 300 lux diffuse illumination
$C_{Rmax} = 360 : 1$	$C_{Rmax} = 39 : 1$

Figure 4: Effect of ambient illumination on the black/white contrast of an LCD-monitor and its directional distribution. White multidirectional isotropic ("diffuse") illumination ($\theta_{max} = 80°$) of approx. 300 lx.

With two light-sources of different aperture (e.g. 1° and 15°) in the same specular setup, the scattering properties of the display-screen can easily be evaluated according to the approach proposed by Kubota [8] and used in ISO 13406-2. The scattering is characterized by the two specular reflectance factors R_{S1} and RS_{15} for the 1° and the 15° source aperture setup respectively.

5 Novel metrology concept

A novel parallel spectrometric metrology approach is introduced for bridging the gap between fast conoscopic measurements (with limited colorimetric precision) and time-consuming sequential mechanical scanning of viewing-directions with precision spectro-radiometric evaluation of chromaticity [9]. This approach uses a multichannel spectrometer for simultaneous measurement of 9 spectra (for 9 angles of inclination) at a specific azimuth angle to speed up directional scanning [10]. It seems it's feasible to adjust both directional resolution and measurement time to the actual requirements without sacrificing spectral resolution.

The new detector-arrangement is directly compatible with two illumination schemes for reproduction of realistic ambient lighting conditions: the DUT can either be illuminated from the specular direction of each "inclination channel" or a hemispherical constant multidirectional illumination can be provided with suppression of the components reflected in the specular direction (matched gloss trap, see [11]). The dynamical properties can be measured with an array of fast photometric detectors which is integrated into the spectrometric detector system [8] or, if required, with a set of fast mono-chromatic detectors tuned to the primary colors R, G and B.

6 Conclusions

The data-sheet information for LCD-screens are not sufficient and often misleading [12]. *Dark-room contrast* values are close to meaningless if the reflectance (BRDF: bidirectional reflectance distribution function) is not known and specified. They should be replaced by the contrast measured under relevant and specified *ambient illumination* conditions [12, 13]. The *viewing-cone* being the range of viewing-directions with not noticeable or acceptable visual artifacts and degradations should be determined by limiting values of the contrast under ambient illumination and by the maximum deviation of the chromaticity for all input signal levels between black and white and for all viewing-directions [7, 13].

A compact set of measurements and evaluations that still provides significant characterization of the visual fidelity of LCD-TV-screens is comprised as follows:

- contrast and color gamut @ DVD(NVD) under darkroom condition,
- variation of contrast and chromaticity with viewing-direction (if possible under ambient illumination),
- contrast and color gamut @ DVD(NVD) under appropriate ambient illumination (e.g. 50 lx for home-cinema conditions, 300 lx for workplace conditions), measurement with 15° aperture source specular to LMD,
- reflectance and scattering characteristics with 1° and 15° aperture source in 15° specular setup (as above).
- fidelity of gray-scale and color-scales vs. electrical driving and viewing-direction (only via achromatic states),
- gray-level transition times, max/min/mean of 20(72) gray-level transition times [9].

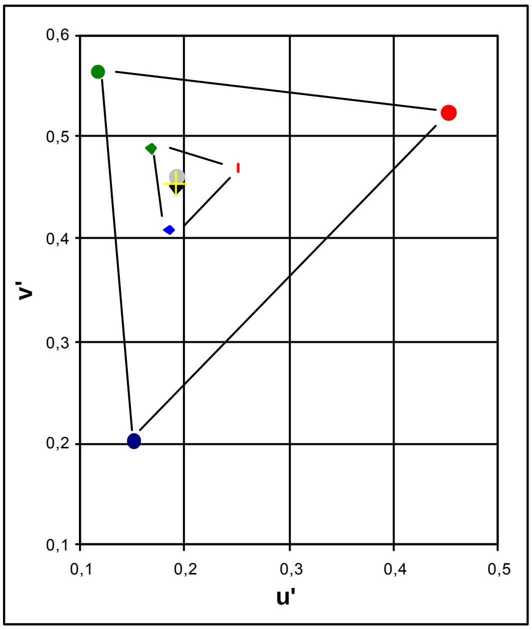


Figure 5: Variation of chromaticity of the primaries R/G/B = 255 and of the achromatic states (R=G=B=255) with ambient illumination (15°-aperture source with 6,840 cd/m^2, 366 lx conical specular illumination, 15° inclination in horizontal plane). The reduction of color-gamut is obvious and the corresponding contrast ratio is reduced to C_R = 1.9.

Acknowledgements

The active hands-on support in all display-metrology issues from Hans-Jürgen Herrmann is most gratefully acknowledged. Both expertise and assistance of J. Laur[12] are highly appreciated.

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