Metrology Issues for LCD-TV

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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 and discussed. A novel concept for scanning of the viewing-directions with simultaneous acquisition of 9 spectra at 9 angles of inclination is introduced as a solution for the dilemma of measurement time and colorimetric precision.

Keywords:

LCD-TV, high-fidelity display, LCD-metrology, visual performance characterization, ISO 13 406, ISO 9241

1 Introduction

LCD-monitors have been successful in replacing CRT-monitors for office work over the last years, even though their product performance specifications (data-sheets) continue to confuse and to mislead the customers [1, 2]. The next challenge for LCD-screens is the huge market for TV and video applications. The essential difference between these two application classes (office work / TV-video)lies in the image contents that are presented to the observer [3]. 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 in this case, 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* (***reality imaging***). As an additional complication, most of the scenes and objects are in motion rather than at a static rest.

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 [4] and the references in there), 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.

In 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. The applicable limiting values that define the borders between acceptable and not acceptable visual performance for a specific application shall then be distilled from adequately conducted ergonomic experiments.

The characterization process for LCD-screens and the resulting characteristic values that describe their visual performance features must be transparent, understandable and significant. The final *figures of merit* should not fool the user (compare the misused concept of the "viewing angle/angel") but provide distinct 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 [6]. In order to fulfill the requirements of this ISO/IEC directive we first have to establish the quantities and conditions that are significant for the display under consideration and its specific application. It is the purpose of this paper to describe a compact set of characteristics (independent of equipment and instrumentation) that are as complete as required in order to characterize the visual performance of LCD-TV-screens. In a second step, a new spectrometer concept is introduced that is helpful for reducing the time required for performing the many colorimetric measurements and evaluations.

The functional requirements for LCD-TV-screens from the users perspective sound quite simple: the display shall provide *high contrast* images with "vivid natural" colors (as a basis for *high visual fidelity*), no changes shall be visible with varying viewing-direction and no artifacts shall be obvious (e.g. false contours), especially in the case of moving images (no *motion artifacts*). Which physical quantities have to be measured under which conditions and which functional dependencies have to be derived and evaluated to make such a performance rating possible on a quantitative basis ? This paper is supposed to provide an answer to that question.

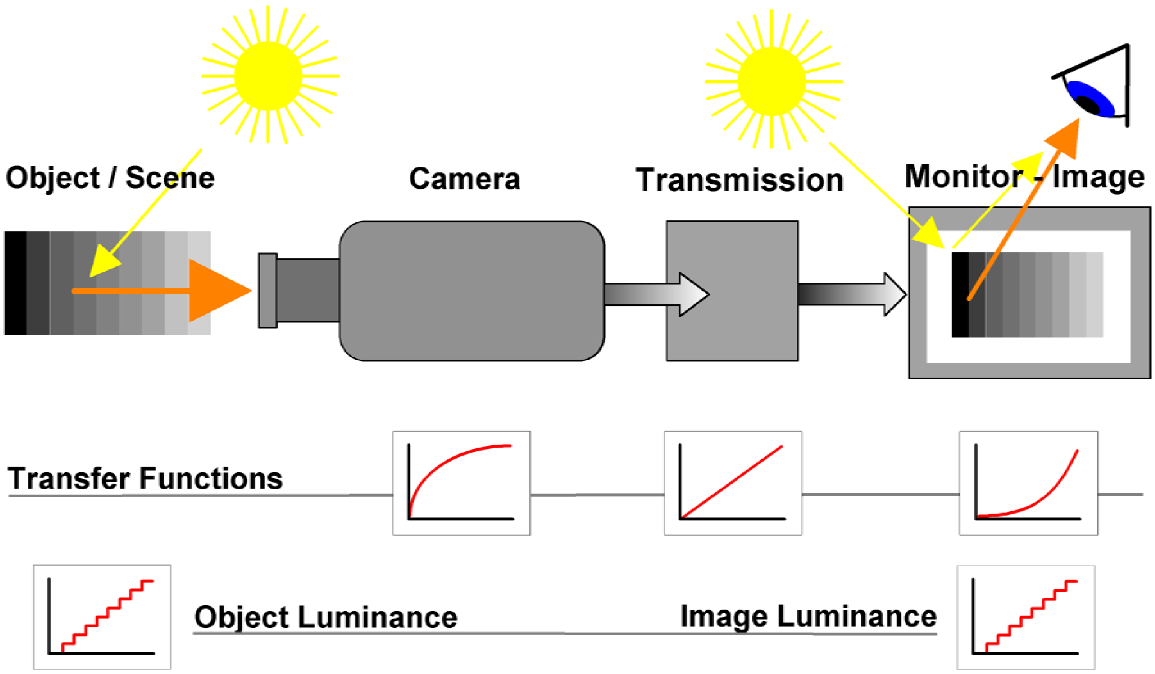

Figure 1: Television/Video transmission chain from object/scene to the presentation on an electronic visual display-screen with indication of the transfer functions of the individual components.

2 Parameters to be evaluated and rated

The metrology for LCD-screens as presented here is focused on their well known weak-spots: the variation of all optical quantities with viewing-direction, not detailing however the limited dynamic capabilities (i.e. slow response times and hold-type performance) of nematic LC-Displays.

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 function* (EOTF) of the display is exactly inverse to the camera transfer-function (see fig. 1). This condition must be fulfilled for all viewing-directions and under ambient illumination (of the display) to ensure *visual fidelity*.

In order to evaluate the *visual fidelity* we have thus to evaluate luminance and chromaticity of the screen (e.g. Y, u', v') as a function of the image content (electrical driving, compare [7, 8]) and of the viewing-direction. These evaluations for the primary colors and for the achromatic states (with a sufficient number of samples over the range of electrical input values) over the range of viewing-directions of interest (e.g. ± 80°) for a sufficient number of azimuth directions requires many measurements and thus, depending on the type of instrumentation used, may be quite time consuming.

3 Electro-optical transfer functions

The relation between the electrical input signals of an LCD-screen (luminance and chrominance signals) and the luminance of the displayed visual information, L, is described by the *electro-optical transfer function* for each primary color channel of the display. In order to assure compatibility of LCD-screens in a transmission chain according to fig. 1, the monitor has to mimic the basic electro-optical characteristic of CRT-screens, because the inverse of the EOTF of CRTs is already applied to the signals in the camera. The intrinsic EOTF of the LCD is modified by electronic computational means (e.g. LUTs, MPUs) that the monitor finally has the required overall EOTF.

Three EOTFs relate the luminance L of the displayed information (L ~ Y) to the electrical input signals as follows (without bias):

$$EOTF_{R/G/B} := L(D_R, D_G, D_B)\ [cd/m^2] \qquad (1)$$

as shown in Fig. 2, or normalized and dimensionless

$$EOTF_{R/G/B} := L(d_R, d_G, d_B)/L_{max} = Y(d_R, d_G, d_B)/Y_{max} = (d_R, d_G, d_B)^{\gamma}$$

with

L_{max}, Y_{max}	max. of luminance L and tristimulus value Y
D_R, D_G, D_B	input values for R, G and B, e.g. [0 -255]
d_R, d_G, d_B	normalized input values for R, G and B [0 -1]
γ	exponent ("*gamma value*") [$\gamma > 1$]

With three primary colors R, G and B and measuring the luminance (or Y) of the screen we obtain 4 EOTFs, one for each primary color (with the two others being zero) and one for the achromatic states with $d_R = d_G = d_B$ as shown in figs. 2 and 3.

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. That means, 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 as constant as possible across the viewing-cone to avoid darker images at oblique viewing directions.

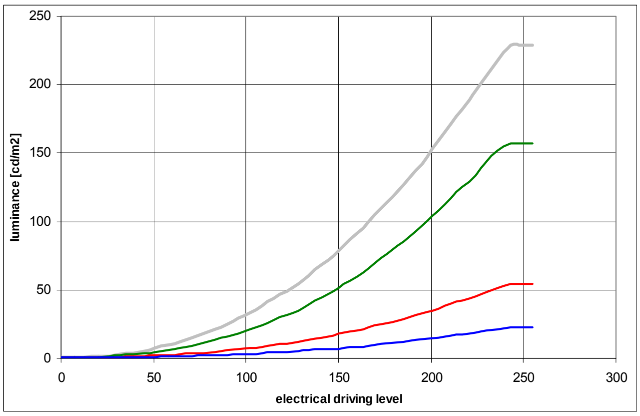

Figure 2: EOTFs (Y) of an LCD monitor versus electrical driving for normal viewing-direction under darkroom conditions for the primary colors R, G and B and the achromatic states.

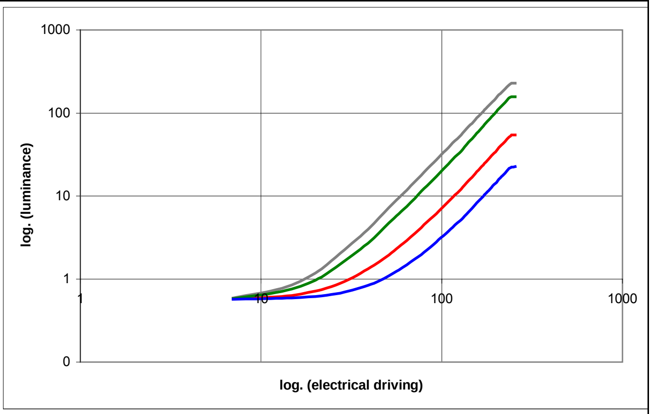

Figure 3: EOTFs (Y) of an LCD monitor versus electrical driving for normal viewing-direction under darkroom conditions. Primary colors R, G and B and the achromatic states. Logarithmic representation of fig. 2. Ideal EOTFs would form straight lines with a slope of γ.

3.1 EOTF artifacts

Two artifacts become obvious in the measured EOTFs of figs. 2 and 3: the curves saturate for input signals above 240 (see fig. 2 and the logarithmic representation reveals a non-zero dark state of approximately 0.6 cd/m^2 (see fig. 3 caused by the non-zero transmission of the LCD.

Spectra of transmission 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 [9, 10]:

- optical crosstalk due to non-ideal spectral separation of the primaries,
- electrical crosstalk due to capacitive coupling between the primary colors.

One basic property of the EOTFs can be checked via luminance differences between gray-levels: a necessary condition is that each EOTF and its first derivative must be increasing in a monotonous way with the input signal, thus, the second derivative (or difference quotient) must be positive for all driving signal levels and all viewing-directions. If this condition is not fulfilled and depending on the amount of deviation, chromaticity distortions can become visible. This is still the case with some computer monitors, especially when the contrast controls are set to obtain a high contrast between the black and white state (a suitable target for a visual test of EOTF distortions is the "Color & gray-scale inversion target" described in the VESA FPDM Standard, section A112-4). Straight-forward error metrics can be used for further quantitative rating of EOTF distortions [11, 12], e.g. the rms-error which is minimized during the numerical evaluation of the value of the exponent gamma. Since the numerical value of TV-gamma is specific for each region on this earth, it has to be evaluated (and adjusted to the locally required value), e.g. according to the recommendations of the ITU [13]. A thorough discussion of the various models for the EOTF (e.g. GOG, GOGO, etc.) is given by Deguchi, et. al. [14] and by Sasaki, et. al. [15].

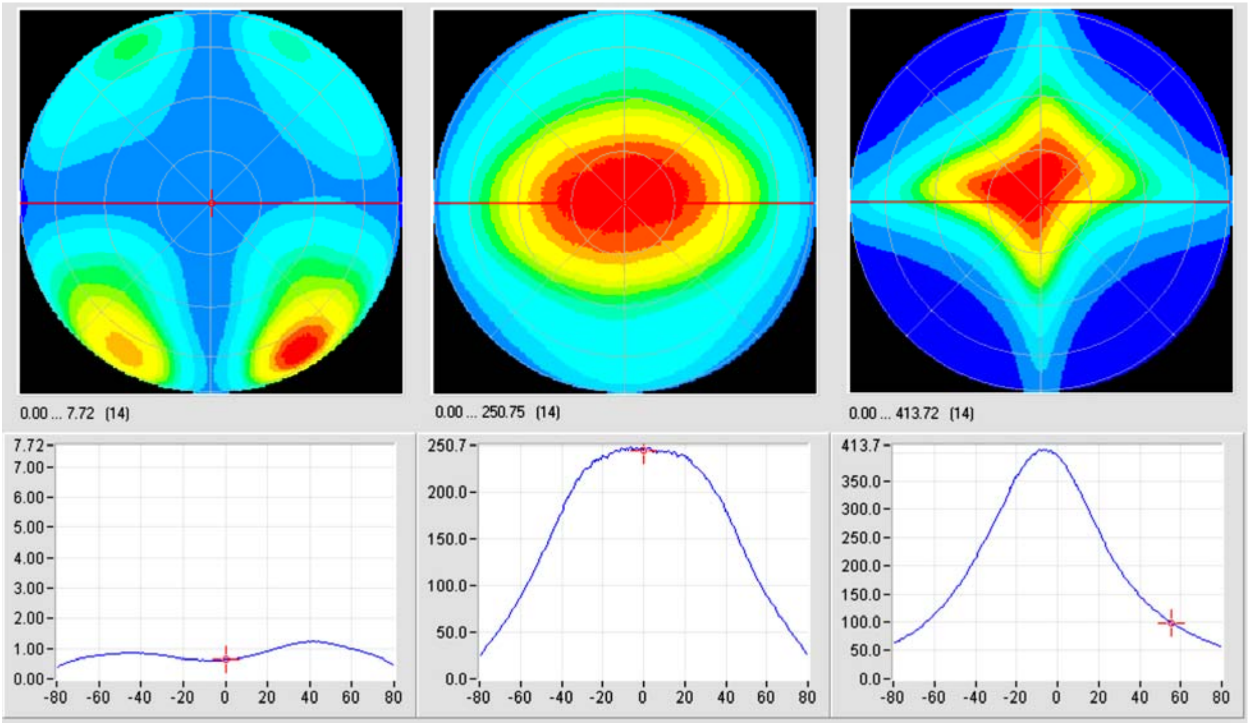

Figure4: Luminance of dark state (left), bright state (center) and the resulting luminance contrast ratio, C_R (right) in a polar coordinate system.

3.2 Additivity of primaries

The general form of the EOTFs in terms of the tristimulus values of the displayed image content comprises the primary transform matrix M for colorimetric characterization of electronic displays with three primaries and is given by [9]:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \cdot \begin{bmatrix} R(d_R) \\ G(d_G) \\ B(d_B) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \qquad (2)$$

with $R(d_R)$, $G(d_G)$, $B(d_R)$ — R, G, B values of image content = f(electrical input)

$R/G/B(d_{R/G/B}) = c_{R/G/B}*(d_{R/G/B\text{-}0} + d_{R/G/B})^{\gamma}$ — GOG-model, nonlinear part of EOTF

with c_R, c_G, c_B — constants (determining the chromaticity of white)

X, Y, Z (X_0, Y_0, Z_0) — tristimulus values of display (in black-state)

X_R, X_G, X_B, Y_R, Y_G, Y_B, Z_R, Z_G, Z_B — coefficients of primary transform matrix, M

If this relation (GOG-model) is adequate for accurate colorimetric characterization of a specific type of LCD-screen, i.e. if the basic additivity is sufficiently fulfilled, has to be evaluated for each display by comparing the tristimulus values corresponding to the maximum values of the primaries to the tristimulus values of the full-white state as shown in table 1. The resulting errors should be as small as possible and not exceed some percent to assure good additivity of the primaries. Alternative models for the EOTF comprise S-shaped curves, polynomials, matrix models and LUTs (look-up tables) as discussed in detail by Tamura [9].

	X	Y	Z
R	99,33	50,59	3,39
G	68,83	146,29	23,41
B	37,33	21,49	207,01
Sum	205,49	218,37	233,81
White	203,33	215,29	230,01
Error	1,05%	1,41%	1,63%

Table 1: evaluation of the additivity of the measured sample LCD-screen

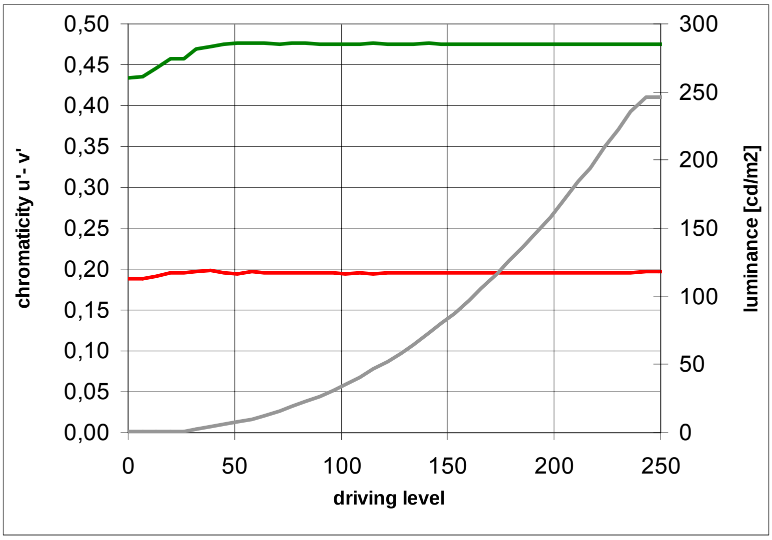

Figure 5: EOTF (Y) and chromaticity of an LCD-monitor versus electrical driving for normal viewing-direction under darkroom conditions, $\Delta u'_{max}$= 0,0089, $\Delta v'_{max}$= 0,0414.

The EOTFs of the three primary color channels must be well synchronized in order to assure proper additivity and thus stable colors that do not show chromatic changes with electrical driving. In addition, for assuring visual fidelity, synchronization and balance of the three EOTFs must be independent of the *viewing-direction*.

Based on the basic requirement of RGB-additivity we can evaluate the chromatic fidelity of LCD-screens with respect to electrical driving and viewing-direction by restricting ourselves to the ***analysis of the gray-states*** only instead of measuring the EOTFs individually for each primary color.

The stability of the individual EOTFs with respect to viewing-direction is evaluated via the tristimulus values of a sufficient number of gray-states at different viewing-directions.

The variation of the chromaticity of the achromatic states with electrical driving together with the EOTF (Y) is shown in fig. 7 for the normal viewing-direction under dark room conditions. A shift of chromaticity towards blue can be noticed for input signals smaller than 50 (i.e. for luminance values < 7.8 cd/m^2). The sensitivity of the human visual system for changes in chromaticity decreases with decreasing luminance, so the measured shift towards blue remains fairly unnoticed.

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.

The ***viewing-direction*** is defined by two angles, the angle of inclination θ (from the display normal), and the azimuth ϕ.

The ***viewing-cone*** (VC) in the most general sense is a range of viewing-directions defined by

- geometric considerations [compare 16, fig. 2] or by
- limiting values of visual target quantities (e.g. minimum contrast, maximum acceptable chromaticity difference $\Delta u'v'_{max}$, etc.).

In the case of LCD-TVs the *viewing-cone* is defined as 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 assume and maintain a quite fixed position 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 ($\theta_{max} = 90°$) as it is the case with CRTs (at least theoretically). The geometrical distortions resulting from oblique observation however (foreshortening, reduction of 29% at $\theta = 45°$) are annoying or even disabling in work-situations but probably acceptable for entertainment purposes (compare [16]).

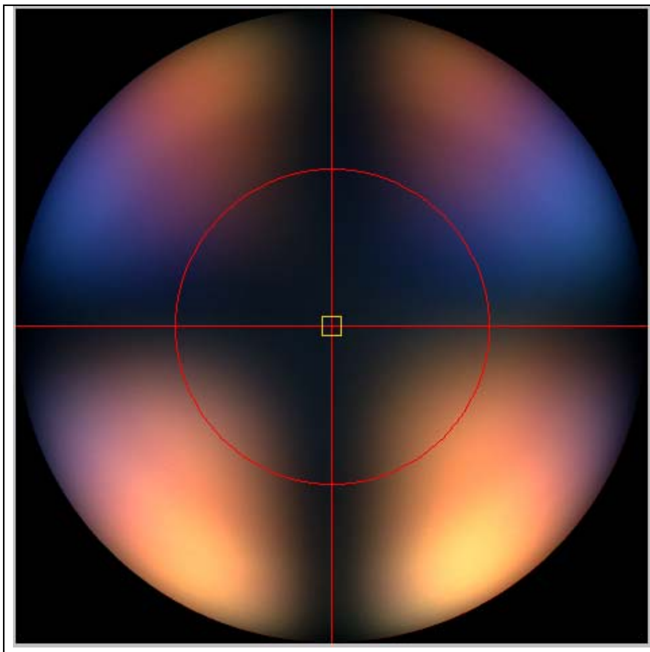

Figure 6: Chromaticity variation of the black-state ($d_R=d_G=d_B=0$) with viewing-direction. The diagonal planes show a pronounced shift of chromaticity towards blue (i.e. decrease of v').

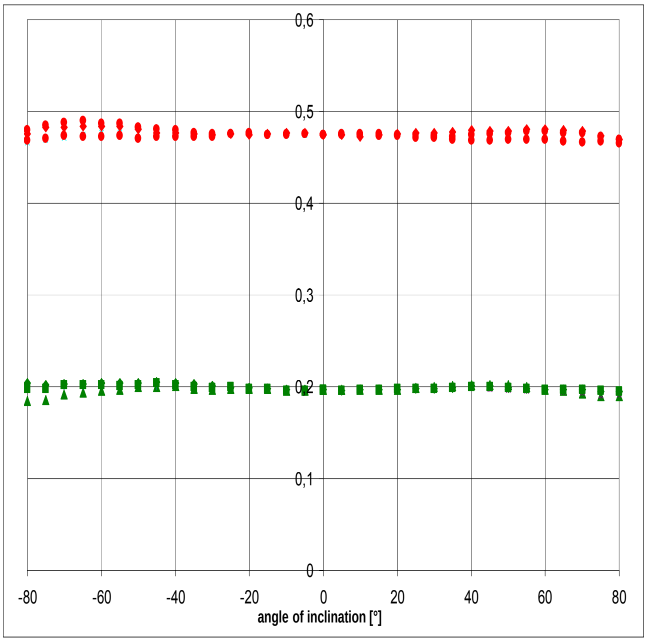

Figure 7: Variation of chromaticity, u', v', with viewing-direction for azimuth angles ϕ = 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° for the full-white state ($d_R=d_G=d_B=255$) under darkroom conditions.

The v*iewing-cone for TV-applications* shall 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 which are most critical for some LCD-effects [17]). 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 [18]).

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

5 Specification of contrast

In data-sheets of LCD-monitors and of TV-sets misleading naive statements for *contrast* can often be found, usually specified by impressive numerical values (e.g. C_R = 450:1). In order to transform such "contrast-numbers" into distinct and 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 viewing-directions (viewing-cone, VC),
- ambient illumination conditions (illuminance level, spectrum, [daylight, incandescent], geometry of illumination).

6 Effect of ambient illumination

Most of the impressive "contrast-numbers" available in data sheets today, even though this is not mentioned explicitly, 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 to be able to make 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 arrangement with the source set to the specified direction of light incidence, which is 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 - 400 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 light-source 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 C_R = 1.9:1.

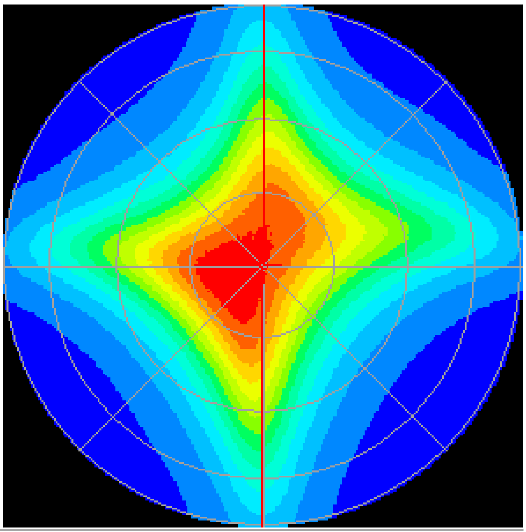	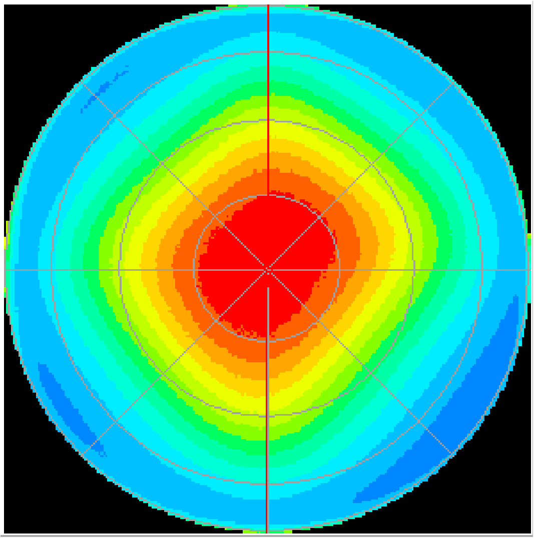
Darkroom Contrast	Contrast @ 300 lux, diffuse illumination
C_{Rmax} = 360	C_{Rmax} = 39

Figure 8: Effect of ambient illumination on the black/white contrast of an LCD-monitor and its directional distribution in a polar coordinate system. White multidirectional quasi-isotropic ("diffuse") illumination (θ_{max} = 80°) of approx. 300 lx.

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. 9.

With two light-sources of different aperture (e.g. 1° and 15°) in the same specular setup, the scattering properties of the TV-screen can easily be evaluated according to the approach proposed by Kubota [19] and used in ISO 13406-2. The scattering is characterized by the two specular reflectance factors R_{S1} and R_{S15} for the 1° and the 15° source aperture respectively. For non-scattering samples, $R_{S1} = R_{S15}$ and the difference between both quantities is increasing with the amount of scattering. The values obtained for our sample screen are: $R_{S1} = 5.0\ 10^{-4}$, $R_{S15} = 3.4\ 10^{-2}$.

7 Time budget considerations

For accurate colorimetric characterization of LCD-screens it is required to evaluate the tristimulus values for a sufficient number of input signal levels (achromatic states, $d_R=d_G=d_B$) for a sufficient number of viewing-directions (e.g. 9*36 for steps of 10° for both θ and ϕ at $\theta_{max}=80°$ and $\phi_{max}=350°$). The choice of 33 driving levels yields 33*9*36 = 10,692 spectra that have to be measured. With 5 s for each single measurement this procedure will take 14.85 hours to complete.

8 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 [20, 21]. 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 [22].

The multichannel spectrometer alone reduces the measurements by a factor of 9. A further efficient reduction of measuring time can be achieved by reduction of the azimuth-angles from e.g. 36 to 8 with $\Delta\phi = 45°$). A measurement with these parameter settings can be completed in about 22 minutes, compared to 198 minutes when each spectrum is acquired individually. So it's feasible to adjust directional resolution and measurement time to the actual requirements without sacrificing spectral resolution.

The detector-arrangement shown in fig. 10 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 [20, 21]). The dynamical properties of the DUT can be measured with an array of fast photometric detectors which is integrated into the spectrometric detector system [22].

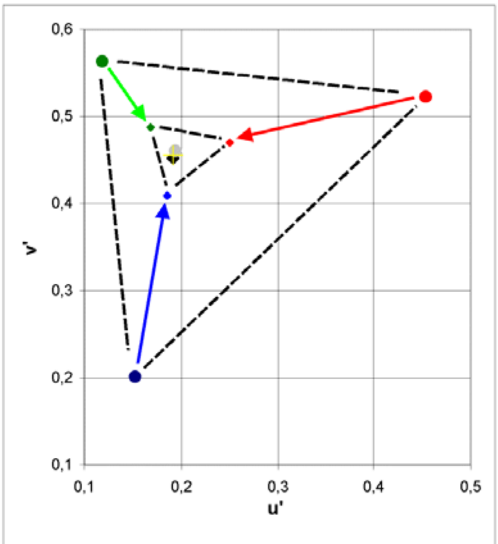

Figure 9: Variation of chromaticity of the primaries $d_R/d_G/d_B = 255$ and of the achromatic states ($d_R=d_G=d_B=255$) with ambient illumination (15°-aperture source with 6,840 cd/m^2, 366 lx illumination, 15° inclination in horizontal plane). The reduction of color-gamut is obvious and the corresponding contrast ratio is reduced from $C_R = 305$ to $C_R = 1.9$.

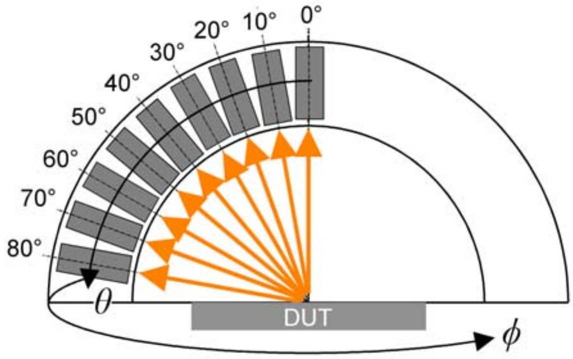

Figure 10: Concept of the *multidirectional spectral measurement:* 9 spectra are measured simultaneously at a specific azimuth angle in the range of 0°≤ θ≤ 80°. Motorized inclination of the array of receivers within Δθ≤10° enables scanning of the angle of inclination, θ, with high resolution.

9 Measurements & Evaluations

A compact set of measurements and evaluations that still provides significant characterization of the visual fidelity of e.g. LCD-TV-screens requires only $N_{ts} = N_{ED} * N_\theta * N_\phi$ tristimulus values to be measured as summarized in table 3 (with N_{ED} : number of driving levels, N_θ : number of inclination angles, N_ϕ : number of azimuth angles).

	Measured quantities	Test-patterns	Parameter 1	Parameter 2	ambient illumination
1	X, Y, Z	full-screen gray-states	electrical driving	viewing direction	darkroom condition optionally: suitable reproduction of ambient illumination
2	X, Y, Z	full-screen black, white red, green, blue	electrical driving		15° aperture source in specular direction
3	Luminance L	backlight OFF or full-screen black (with correction)	aperture of light-source (1° & 15° aperture)		1° & 15° aperture source in specular direction
4	L = f(time)	full-screen gray-states	start-level	end-level	dark room condition

Table 3: Measured quantities, test-patterns and parameters of the compact set of measurements.

From these measurements the following results are evaluated:

1 **fidelity of gray-scale and chromaticity vs. electrical driving and viewing-direction**
with: sufficient number of gray-states and viewing-directions,
see fig. 5: luminance L = f(electrical driving$|_{viewing\text{-}direction}$
chromaticity (u'v') = f(electrical driving$|_{viewing\text{-}direction}$
and table 1 $\Delta u'v'_{max}$ for selected gray-states
value of exponent gamma for any viewing-direction

2 **contrast and color gamut @ DVD (or NVD) under darkroom condition**
with: screen full-black, full-white, full-R, G and B,
contrast ratio C_R = 305,
color gamut: see outer triangle of fig.9,
chromaticity of white: u'= 0.1972, v'= 0.4699.

2 **contrast and color gamut @ DVD (or NVD) under ambient illumination**
measurement with 15° aperture source specular to LMD,
with: screen full-black, full-white, full-R, G and B,
contrast ratio C_R = 1.9 (for 15° aperture source @ 6,840 cd/m^2 in specular direction),
color gamut: see inner triangle of fig.9.

2 **variation of contrast with viewing-direction**
with: screen full-black, full-white,
see fig. 4 sample screen (dark-room) and e.g. fig. 8 (typical example, not for sample screen).

3 **reflectance and scattering characteristics** with 1° and 15° aperture source in 15° specular setup,
with: backlight OFF,
$R_{S1} = 5.0\ 10^{-4}$, $R_{S15} = 3.4\ 10^{-2}$
and additionally,

4 **gray-level transition times** with specification of Max/Min/Mean of 20 (or 72) transition times [11],
with: 5 or 9 gray-states, (not measured here).

10 Conclusion

The data-sheet information for LCD-screens for television and video applications are often not providing the required characteristics and are misleading and confusing [1, 2, 23]. They are often more focused on the market-barkers hype of numbers than on meaningful and significant characteristics (see also [24]). *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 (compare [25]), since the effect of all measures applied for suppression of reflections from the display surface becomes obvious from the reduction of e.g. contrast and color-gamut as induced by ambient illumination. The *viewing-cone* being the range of viewing-directions with not noticeable or acceptable visual artifacts and degradations should be determined by reasonable limiting values for the contrast and/or by the maximum deviation of the chromaticity, $\Delta u'v'$, for all input signal levels between black and white and for all viewing-directions [3, 11].

The compact set of measurement and evaluations presented here provides all parameters for a meaningful and significant characterization of high-fidelity LCD-screens at a minimum of time and efforts.

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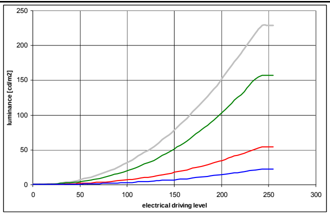
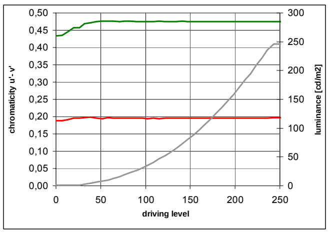
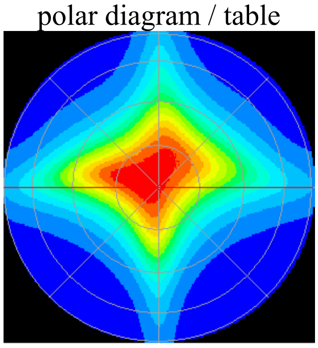
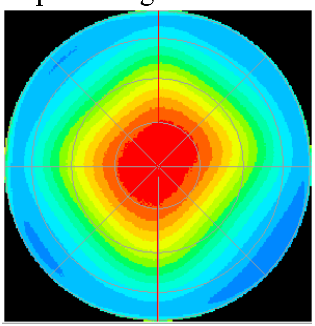
Characteristic	Darkroom	With ambient illumination
Chromaticity vs. viewing-direction @ electrical driving	polar diagram, e.g. $\Delta u'v'=f(\theta,\phi)$ @ (d_R, d_G, d_B) (related to a reference direction) table: $u', v'=f(\theta,\phi)$ @ (d_R, d_G, d_B) or $Max[\Delta u'v'(\theta,\phi)]$ @ (d_R, d_G, d_B)	
Luminance vs. electrical driving @ viewing-direction	 value of gamma (gray) = 2.23 ± 0.02	
Chromaticity vs. electrical driving @ viewing-direction	$u', v'=f(d_R, d_G, d_B)$ @ (θ,ϕ) or $Max[\Delta u'v'(d_R, d_G, d_B)]$ @ (θ,ϕ) 	
Contrast @ viewing-direction	$C_R = 305$	$C_R = 1.9$
Color gamut @ viewing-direction	u'(R) = 0.4532 v'(R) = 0.5231 u'(G) = 0.1184 v'(G) = 0.5635 u'(B) = 0.1528 v'(B) = 0.2008 see outer triangle of fig. 9	u'(R) = 0.2509 v'(R) = 0.4697 u'(G) =0.1682 v'(G) = 0.4885 u'(B) = 0.1855 v'(B) = 0.4098 see inner triangle of fig. 9
Chromaticity of white	u'= 0.1972 v'= 0.4699	D65 (for comparison) u'= 0.1978 v'= 0.4683
Reflectance / scattering		$R_{S1} = 5\ 10^{-4}$ $R_{S15} = 3\ 10^{-2}$
Contrast = f(viewing-direction)	polar diagram / table 	polar diagram / table 
Additivity	**X** **Y** **Z** **R** 99,33 50,59 3,39 **G** 68,83 146,29 23,41 **B** 37,33 21,49 207,01 **SUM** 205,49 218,37 233,81 **White** 203,33 215,29 230,01 **Error** **1,05%** **1,41%** **1,63%**	
Dynamics	Max, Min, Mean of 5x5 or 9x9 matrix	

Report sheet for a complete set of measurements and evaluations