Measurement of Visual Resolution of Display Screens

Michael E. Becker
Display-Messtechnik&Systeme
D-72108 Rottenburg am Neckar - Germany

Abstract

This paper explains and illustrates the meaning of luminance modulation (aka Michelson contrast) of visual display screens as basis for the perception of presented visual information and as basis for objective visual performance evaluation and rating of display screens according to the 2016 IDMS updates.

Keywords

visual perception limits, visual acuity, contrast metrics, lateral and angular resolution, optimum viewing distance, IDMS

1. Introduction

Technical specifications of display screens used as computer monitors or as TV-video screens should inform the user about the ability of the display to reproduce fine details of the image content to be presented to the observer.

The finest details that can be displayed will be of similar size as the smallest entities of the display that can be electrically controlled to reproduce the full range of luminance and chromaticity of the display screen. In the case of flat-panel displays with fixed matrix structures the smallest entity able to reproduce the full range of luminance and chromaticity is usually called pixel (short form for "picture element"). In CRT monitors however, the pixels were not rigidly coupled to the individual phosphor dots, but they were rather determined by the diameter and the profile of the electron beam and its timing. So the width of lines (with near Gaussian profile) and their spacing could be controlled electrically in CRTs, but these are both fixed in flat-panel displays by the manufacturing process and the very nature of the device.

Even in flat-panel displays the ability to independently control individual pixels and sub-pixels may be limited by electrical effects (crosstalk) and by scattering of light from one sub-pixel to an adjacent one (halation). That means that the visual resolution of flat-panel display screens is not directly given by the addressability which is commonly specified as the dimensions of the sub-pixel matrix (e.g. 1920x1080x3 for HD and 3840x 2160x3 for UHD), see [1].

Additionally, the traditional way of composing one square-shaped pixel from three stripe-shaped sub-pixels, each providing one of the primary colors, R, G and B, is recently being complemented by alternative sub-pixel architectures (e.g. RGBY, RGBW, PenTile [2]) and new techniques of grouping sub-pixels in the process of presenting image information on the display screen (sub-pixel rendering).

Sub-pixel rendering techniques can be applied in the temporal domain (e.g. with projectors by presenting several sub-frames within one frame) and in the spatial domain (with direct view displays based on spatial integration of the human visual system), they are forming pixels on demand, depending on the image content, from adjacent sub-pixels, thus abandoning the fixed relation between sub-pixels and pixels previously common to flat-panel displays.

This paper describes the effect of alternative sub-pixel layouts on procedures for measurement and evaluation of the visual resolution of direct-view display screens.

2. Recognition of visual information: Contrast is the key

Recognition of visual information by human beings is largely related to *contrast*, which is the "difference in appearance of two parts of a field seen simultaneously" according to the CIE ILV (International Lighting Vocabulary, [3]).

The human visual system has been optimized for recognition of contrast over millions of years of evolution, since the contrast of reflective objects and scenes (e.g. our natural environment) remains fairly constant over a wide range of *illuminance* levels, i.e. from bright daylight to dim twilight and indoor levels.

In this paper we restrict ourselves to discussing *contrast* based on luminance differences (variations). The contrast of two fields seen simultaneously is determined by the luminance levels of these fields (L_H, L_L) from which several expressions for *contrast* can be obtained, e.g. the luminance ratio (L_H/L_L), the relative luminance difference ($[L_H-L_L]/L_L$), the luminance modulation ($[L_H-L_L]/[L_H+L_L]$, aka. *Michelson contrast* (usually used close to the perception threshold) and the Weber contrast ($\Delta L/L$). When specifying contrast it thus seems to be indispensable to also specify which variant of the listed types of contrast is considered.

2.1. Limits of perception

Practical experience shows that it is increasingly difficult to read small characters with decreasing perceived brightness and with decreasing apparent size of the characters. A daylight adapted human eye (30 to 30,000 cd/m^2) requires a contrast modulation, C_M, of about 0.5% for luminance differences between not-too-small fields to be just visible. Additionally, the limit of visual discrimination of a visual target with size is determined by the angle that it subtends at the eye of the observer. This angle is given by

$$\textit{visual angle} = 2\cdot\arctan(\text{height of feature} / (2\cdot\text{viewing distance}))$$

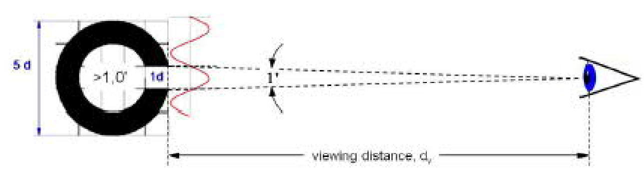


Figure 1: The human eye can recognize high-contrast features - here the gap of the C-ring - that subtend an angle of about one minute of arc (1°/60 = 0.017°).

Measurement of Visual Resolution of Display Screens

Michael E. Becker
Display-Messtechnik&Systeme
D-72108 Rottenburg am Neckar - Germany

Abstract

This paper explains and illustrates the meaning of luminance modulation (aka Michelson contrast) of visual display screens as basis for the perception of presented visual information and as basis for objective visual performance evaluation and rating of display screens according to the 2016 IDMS updates.

Keywords

visual perception limits, visual acuity, contrast metrics, lateral and angular resolution, optimum viewing distance, IDMS

1. Introduction

Technical specifications of display screens used as computer monitors or as TV-video screens should inform the user about the ability of the display to reproduce fine details of the image content to be presented to the observer.

The finest details that can be displayed will be of similar size as the smallest entities of the display that can be electrically controlled to reproduce the full range of luminance and chromaticity of the display screen. In the case of flat-panel displays with fixed matrix structures the smallest entity able to reproduce the full range of luminance and chromaticity is usually called pixel (short form for "picture element"). In CRT monitors however, the pixels were not rigidly coupled to the individual phosphor dots, but they were rather determined by the diameter and the profile of the electron beam and its timing. So the width of lines (with near Gaussian profile) and their spacing could be controlled electrically in CRTs, but these are both fixed in flat-panel displays by the manufacturing process and the very nature of the device.

Even in flat-panel displays the ability to independently control individual pixels and sub-pixels may be limited by electrical effects (crosstalk) and by scattering of light from one sub-pixel to an adjacent one (halation). That means that the visual resolution of flat-panel display screens is not directly given by the addressability which is commonly specified as the dimensions of the sub-pixel matrix (e.g. 1920x1080x3 for HD and 3840x 2160x3 for UHD), see [1].

Additionally, the traditional way of composing one square-shaped pixel from three stripe-shaped sub-pixels, each providing one of the primary colors, R, G and B, is recently being complemented by alternative sub-pixel architectures (e.g. RGBY, RGBW, PenTile [2]) and new techniques of grouping sub-pixels in the process of presenting image information on the display screen (sub-pixel rendering).

Sub-pixel rendering techniques can be applied in the temporal domain (e.g. with projectors by presenting several sub-frames within one frame) and in the spatial domain (with direct view displays based on spatial integration of the human visual system), they are forming pixels on demand, depending on the image content, from adjacent sub-pixels, thus abandoning the fixed relation between sub-pixels and pixels previously common to flat-panel displays.

This paper describes the effect of alternative sub-pixel layouts on procedures for measurement and evaluation of the visual resolution of direct-view display screens.

2. Recognition of visual information: Contrast is the key

Recognition of visual information by human beings is largely related to *contrast*, which is the "difference in appearance of two parts of a field seen simultaneously" according to the CIE ILV (International Lighting Vocabulary, [3]).

The human visual system has been optimized for recognition of contrast over millions of years of evolution, since the contrast of reflective objects and scenes (e.g. our natural environment) remains fairly constant over a wide range of *illuminance* levels, i.e. from bright daylight to dim twilight and indoor levels.

In this paper we restrict ourselves to discussing *contrast* based on luminance differences (variations). The contrast of two fields seen simultaneously is determined by the luminance levels of these fields (L_H, L_L) from which several expressions for *contrast* can be obtained, e.g. the luminance ratio (L_H/L_L), the relative luminance difference ($[L_H-L_L]/L_L$), the luminance modulation ($[L_H-L_L]/[L_H+L_L]$, aka. *Michelson contrast* (usually used close to the perception threshold) and the Weber contrast ($\Delta L/L$). When specifying contrast it thus seems to be indispensable to also specify which variant of the listed types of contrast is considered.

2.1. Limits of perception

Practical experience shows that it is increasingly difficult to read small characters with decreasing perceived brightness and with decreasing apparent size of the characters. A daylight adapted human eye (30 to 30,000 cd/m^2) requires a contrast modulation, C_M, of about 0.5% for luminance differences between not-too-small fields to be just visible. Additionally, the limit of visual discrimination of a visual target with size is determined by the angle that it subtends at the eye of the observer. This angle is given by

$$\textbf{\textit{visual angle}} = 2\cdot\arctan\,(\text{height of feature} / (2\cdot\text{viewing distance})\,)$$

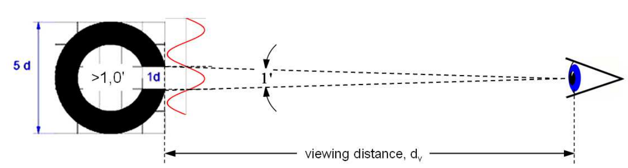
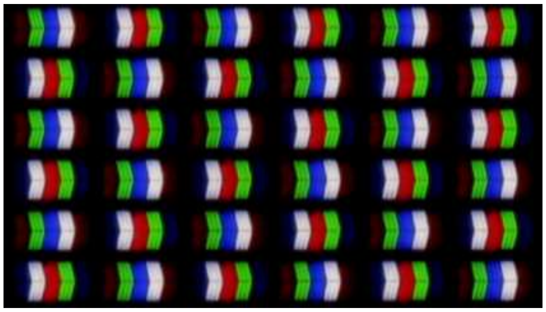
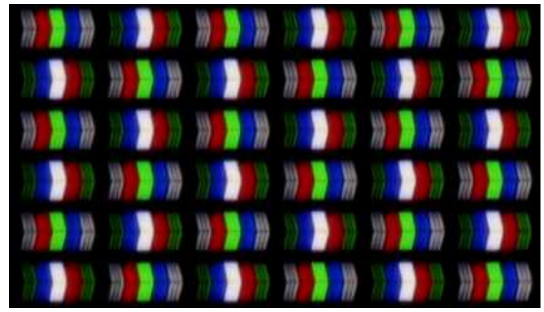


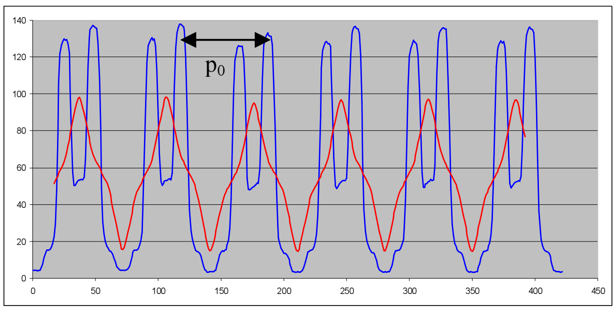
Figure 1: The human eye can recognize high-contrast features - here the gap of the C-ring - that subtend an angle of about one minute of arc (1°/60 = 0.017°).



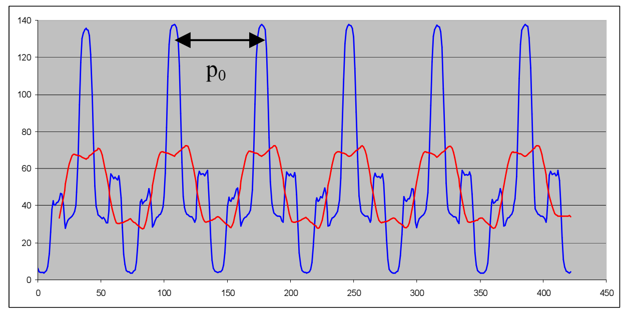
Sub-pixel pattern of RGBW display - phase 1



Sub-pixel pattern of RGBW display - phase 2



Luminance profile (blue curve) and averaged luminance profile (red curve) for a phase-1 achromatic grille pattern



Luminance profile (blue curve) and averaged luminance profile (red curve) for a phase-2 achromatic grille pattern

Figure 2: Grille-patterns of achromatic vertical lines (top) displayed on an RGBW-screen and the corresponding luminance profiles (bottom, blue curve). The period corresponding to the lowest spatial frequency, p_0, is the same for both phases of the grille pattern. The red curve is obtained by application of a *moving window average* with a window dimension of $p_0/2$. It represents what the eye of an observer perceives from the optimum viewing distance according to section 2.1.

The visual angle of one minute of arc (1' = 1°/60) is the accepted *average value* for *normal visual acuity* under the conditions of good target contrast and photopic adaptation of the eye (daylight vision). That means that the human eye performs an integration over an angle of about one minute of arc if no hyperacuity is involved (e.g. perception of the displacement of two parallel lines, called *vernier acuity*). A *visus of 1* means that a visual target feature with high contrast subtending an angle of 1 minute of arc (1' = 1°/60) can just be recognized [4]. This value does significantly vary with age and from individual to individual.

It is practical to select the viewing distance to a display screen in such a way that we see a uniform white area when all sub-pixels are activated and thus do not perceive details of the sub-pixel structure. A display screen with a pixel pitch of 0.3 mm should thus be watched ideally from a distance of (only slightly) more than 1031 mm in order to fulfill that condition. This is also the ***optimum viewing distance*** since any further increase reduces the visibility of fine image details. If the same display screen is observed from double the viewing distance (2062 mm) three out of four pixels do not contribute to forming fine image details because the eye of the observer now integrates over four pixels (two horizontally, two vertically) which cannot be resolved individually. In other words, a UHD screen visually becomes an HD-screen when viewed from two times the ideal viewing distance because the visual angle now subtends four pixels instead of one.

2.2. How well does a display screen reproduce input signals ?

Resolution is often incorrectly specified in display data sheets as the "number of individually addressable and controllable pixels", e.g. 1920 x 1080 or 3840 x 2160. This however only specifies the dimensions of the display pixel array or the *addressability* of the display. *Resolution* however should specify how well the smallest details presented on the display appear separate and distinct, i.e. how well the screen can actually display fine details of images. This ability may be limited by electrical interactions between sub-pixels and pixels (electrical crosstalk) and by scattering of light from one sub-pixel to an adjacent one (halation or optical crosstalk).

The *visual resolution* of display screens, i.e. the ability to render fine image details is usually evaluated with achromatic grille test-patterns, i.e. parallel lines of black and white (or shades of grey) in the vertical and horizontal direction. In order for the pixels, arranged in columns or rows, to be distinctly visible, the contrast of a grille pattern must be above the threshold of perception. The higher the contrast of the grille pattern the better is the visual performance of the display.

However, other sub-pixels layouts than just RGB are possible and realized in commercially available display products. A yellow sub-pixel may be added, for example, in an attempt to increase color gamut or white sub-pixels may be added (RGBW) for improving the maximum luminance (and thus the perceived brightness) of the display screen, respectively, according to the claims of the manufacturers.

2.2.1. Visual resolution in case of standard sub-pixel layouts

The IDMS (*International Display Measurement Standard* V1.03, issued by the *International Committee for Display Measurement*, ICDM, in 2012) describes a widely accepted method for evaluation of display resolution in section 7, clause 7.2 and 7.8 ("*resolution from contrast modulation*"). The method is based on the variation of luminance in horizontal and vertical direction, i.e. parallel to the display rows and columns. Great care has to be exercised in order to measure these luminance distributions with imaging light measurement devices (ILMDs) accurately without errors and artefacts. The ICDM describes procedures, methods and precautions on how to carry out these measurements.

A display screen with a visual resolution of 3840 x 2160 must be able to simultaneously present 1920 black and 1920 white lines with a luminance modulation (Michelson contrast) that is at least sufficient for the intended application case (i.e. 25% for TV and video and 50% for computer monitor use). The updated section 7.2 requires reporting of the Michelson contrast for maximum number of grille lines to avoid obfuscation of the actual display performance by application of a threshold (binary decision).

2.2.2. Visual resolution in case of non-standard sub-pixel layouts

An alternative sub-pixel layout that is available on the market makes use of RGBW sub-pixels with a horizontal shift of two sub-pixels with respect to the adjacent lines. Achromatic black and white vertical lines of minimum width can be rendered on such displays e.g. as shown in Fig. 2.

In 2015 some display metrology laboratories started to notice conceptual conflicts when trying to apply the procedures of the IDMSv1p03b, June 2012, to display screens with non-standard sub-pixel arrangements (e.g. RGBW). That version of the IDMS had been written for computer monitors with a distinct fixed relation between sub-pixels and pixels of the display. For that class of devices a pixel is defined as the smallest unit that can display the full range of luminance and chromaticity. That definition would require 4 sub-pixels for a pixel in the case of RGBW.

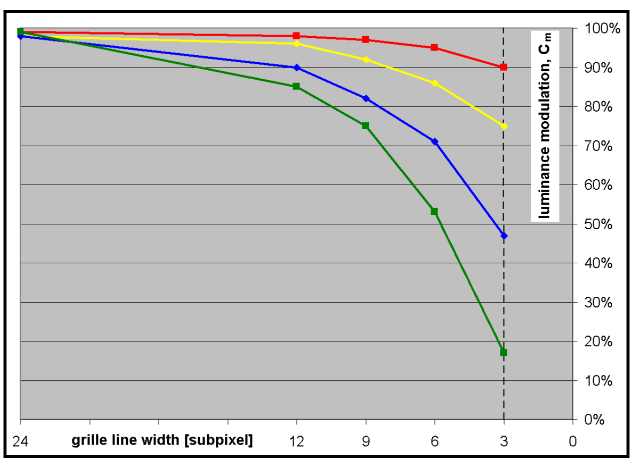


Figure 3: Illustrative example for the variation of achromatic grille luminance modulation with line width (specified by the number of sub-pixels) for different display screens.

2.2.3. Luminance modulation vs. grille line-width

If a display screen features a luminance modulation for the smallest grille line width that is above a threshold value (e.g. above 50% for the yellow and red curves in Fig. 3), application of the threshold hides the difference in luminance modulation that is obvious in Fig. 3, because with increasing contrast (i.e. luminance modulation), also the quality of rendering fine image details is increasing. For a display that did not reach the required threshold contrast a linear interpolation was used for determination of a hypothetical resolution which however can not be displayed on the screen (see IDMS 2012, 7.8, Fig. 1).

3. The 2016 updates of the IDMS

After a period of discussions, the ICDM on May 24, 2016 finally accepted a series of editorial comments and explanations (7p0-01-20160524.pdf, 7p2-01-20160524.pdf and 7p8-01-20160524.pdf) that are meant to provide a safe basis for those who have to perform visual resolution measurements during the time period until the next version of the IDMS will be completed and released.

The updated procedures are based on evaluation of the luminance modulation of achromatic grille test-patterns (both phases) with focus on the smallest grille line width (i.e. highest number of line pairs). The width of the averaging window is unambiguously obtained from the measured luminance profile (fundamental spatial frequency), not from biased or unjustified and not applicable "pixel" definitions). In case of different modulations for both phases of the grille pattern (as illustrated in Fig. 2), the average modulation value has to be calculated and reported. The updated section 7.2 requires reporting of the Michelson contrast for the smallest grille line width to avoid obfuscation by application of thresholds for pass/fail decisions.

The updates also suggest that version 2 of the IDMS will comprise the following details for even more complete specification of the visual resolution of display screens:

1 Replacement of the modulation thresholds by specification of the luminance modulation (e.g. 1920 line-pairs @ m=75%)

as a function of achromatic grille line width specified in units of sub-pixels (as illustrated in Fig. 3) or as number of lines/line-pairs per display width/height.

2 Extension to grille patters of primary colors in combination with black.

4. Light measurement devices

Evaluation of the luminance profiles of the achromatic grille patterns addressed throughout this paper requires spatial oversampling of the sub-pixel matrix of the display under test in order to avoid sampling artefacts that can severely affect the measurements. High magnification usually also means a reduced working distance. So reflections from the objective lens back to the DUT and stray light within the optics of the LMD (lens flare, veiling glare) may introduce considerable errors. The Appendix A2 of the IDMS describes the problems related to the measurement of luminance profiles on the sub-pixel level and provides diagnostics, precautions and approaches to minimize errors.

Such measurements are often carried out with consumer RGB-cameras in combination with a high magnification objective-lens. In that case a calibration is required in order to obtain approximate luminance values from the RGB-channels of the camera (RAW-data processing is required to assure linearity). Such calibrations become too inaccurate and may even fail in the case of RGBW displays.

In order to keep measurement uncertainties as low as possible, simple imaging LMDs with a filter added to achieve the required overall spectral sensitivity according to the spectral luminous efficiency, V(λ), for photopic vision should be used instead of RGB-cameras.

5. The updated measurement procedure

The measurement procedure for *visual resolution* according to the editorial comments and explanations documented in the IDMS updates 7p0-01-20160524.pdf, 7p2-01-20160524.pdf and 7p8-01-20160524.pdf is summarized here as follows.

1 Apply an achromatic grille test-pattern to the display screen starting with e.g. the highest number of lines that can be displayed according to the specified dimensions of the display matrix (addressability). For an UHD screen this is 3840 lines in the vertical direction (1920 black and 1920 white lines) and 1080 line-pairs (2160 lines) in the horizontal direction.

Make sure that no coloration effects occur.

Apply one grille pattern for each phase (odd and even).

2 Record the 2D luminance distribution of the grille patterns with an imaging LMD taking into account the precautions described in IDMS-V1.03 in section A2.

3 Apply averaging along the direction of the grille lines over an integer number of rows or columns (min. 2, better 4) in order to include the effect of sub-pixel shifting between successive columns and rows as illustrated in Fig. 2.

4 From the luminance profiles obtained according to (3) determine the widest modulation period, p_0, which is corresponding to the lowest modulation frequency, as illustrated in Fig. 2. Detailed suggestions on how to achieve this are given in the addendum to IDMS section 7.2 (provided in 7p2-01-20160524.pdf).

5 Perform a *moving window averaging* with a window width of $p_0/2$ according to the procedure described in 7p2-01-20160524.pdf. Detailed suggestions on how to achieve this with e.g. standard spreadsheet software are given in the addendum to IDMS section 7.2 (provided in 7p2-01-20160524.pdf).

Check the correctness of the window width, $p_0/2$, by performing the averaging with a window of width p_0 which must result in a perfectly flat luminance profile.

6 Determine the complete set of local luminance modulation levels from local maxima of the averaged luminance profiles and the adjacent minima (or the other way around) to obtain an average value of luminance modulation for the screen area included in the measurement.

7 Determine the luminance modulation for both phases of the grille pattern (even, odd) and calculate their average value.

8 Report the average luminance modulation together with the width of the grille lines of the test-pattern used, specified e.g. in terms of sub-pixels (or as number of lines/line-pairs per display width/height) even if the threshold level required for the respective application case (25% for TV, 50% for computer monitor) is exceeded.

A typical UHD performance specification would read like this:

1920 vertical line-pairs @ e.g. 75% modulation
1080 horizontal line-pairs @ e.g. 85% modulation

This measurement procedure may be repeated for grille patterns with wider lines in order to evaluate the luminance modulation vs. grille line width as shown in Fig. 3. The most important evaluation however, is done with the maximum number of lines that can be rendered by the display screen with specified contrast). The contrast level required for a specific application may be negotiated between supplier and customer.

6. Discussion

The width of the window used for averaging as introduced here is based on perceptional arguments, it can however as well be understood as a means to get rid of modulations at and below the sub-pixel scale by averaging.

The grille test-patterns used in the procedures described here are applicable to screens that are supposed and able to display characters and line-graphics (i.e. non band-limited content).

An alternative approach to evaluation of ("effective") display resolution based on the slanted edge method according to ISO 12233 is described in section 7.7 of the IDMS-V1.03. The resulting luminance modulation vs. cycles/(display sub-pixel) should be directly comparable to the results obtained with the method described above, but it is much less clear and intuitive.

The author of this paper proposes to replace specification of hypothetical resolutions obtained by linear interpolation by specification of luminance modulation (contrast) obtained for a specific display format (e.g. UHD, 1920 vertical line-pairs @ e.g. 75% modulation, 1080 horizontal line-pairs @ e.g. 85% modulation).

7. Conclusion

The new procedure for determination of the averaging window width for non-standard RGB sub-pixel layouts is independent from any forced pixel definition and thus provides a solid basis for all luminance modulation-based evaluations. Inclusion of the suggestions made here and in the 2016 IDMS updates into the IDMS V2 will make evaluation of display resolution more comprehensive.

8. Acknowledgements

The author would like to thank his colleagues in the display measurement community, especially in the ICDM "spatial sub-committee", for their cooperation, ideas and contributions and their patience during extended and sometimes controversial discussions in 2015/16. Without the due mutual respect and benevolent manners the results described above (i.e. the 2016 updates) would not have been possible.

9. References

[1] IDMS (International Display Measurement Standard V1.03(2012), issued by the SID International Committee for Display Measurement, ICDM

[2] PenTile sub-pixel layouts
http://www.nouvoyance.com/technology.html
https://en.wikipedia.org/wiki/PenTile_matrix_family

[3] CIE S17/E:2011 ILV: International Lighting Vocabulary
http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=845-02-47

[4] http://webvision.med.utah.edu/book/