

PS3.14

DICOM PS3.14 2018b - Grayscale Standard Display Function

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Foreword

This DICOM Standard was developed according to the procedures of the DICOM Standards Committee.

While other parts of the DICOM Standard specify how digital image data can be moved from system to system, it does not specify how the pixel values should be interpreted or displayed. PS3.14 specifies a function that relates pixel values to displayed Luminance levels.

A digital signal from an image can be measured, characterized, transmitted, and reproduced objectively and accurately. However, the visual interpretation of that signal is dependent on the varied characteristics of the systems displaying that image. Currently, images produced by the same signal may have completely different visual appearance, information, and characteristics on different display devices.

In medical imaging, it is important that there be a visual consistency in how a given digital image appears, whether viewed, for example, on the display monitor of a workstation or as a film on a light-box. In the absence of any standard that regulates how these images are to be visually presented on any device, a digital image that has good diagnostic value when viewed on one device could look very different and have greatly reduced diagnostic value when viewed on another device. Accordingly, PS3.14 was developed to provide an objective, quantitative mechanism for mapping digital image values into a given range of Luminance. An application that knows this relationship between digital values and display Luminance can produce better visual consistency in how that image appears on diverse display devices. The relationship that PS3.14 defines between digital image values and displayed Luminance is based upon measurements and models of human perception over a wide range of Luminance, not upon the characteristics of any one image presentation device or of any one imaging modality. It is also not dependent upon user preferences, which can be more properly handled by other constructs such as the DICOM Presentation Lookup Table.

The DICOM Standard is structured as a multi-part document using the guidelines established in [ISO/IEC Directives, Part 2].

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1 Scope and Field of Application

PS3.14 specifies a standardized Display Function for display of grayscale images. It provides examples of methods for measuring the Characteristic Curve of a particular Display System for the purpose of either altering the Display System to match the Grayscale Standard Display Function, or for measuring the conformance of a Display System to the Grayscale Standard Display Function. Display Systems include such things as monitors with their associated driving electronics and printers producing films that are placed on light-boxes or alternators.

PS3.14 is neither a performance nor an image display standard. PS3.14 does not define which Luminance and/or Luminance Range or optical density range an image presentation device must provide. PS3.14 does not define how the particular picture element values in a specific imaging modality are to be presented.

PS3.14 does not specify functions for display of color images, as the specified function is limited to the display of grayscale images. Color Display Systems may be calibrated to the Grayscale Standard Display Function for the purpose of displaying grayscale images. Color images, whether associated with an ICC Profile or not, may be displayed on standardized grayscale displays, but there are no normative requirements for the display of the luminance information in a color image using the GSDF.

2 Normative References

The following standards contain provisions, which, through reference in this text, constitute provisions of this Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Standard are encouraged to investigate the possibilities of applying the most recent editions of the standards indicated below.

[ISO/IEC Directives, Part 2] ISO/IEC. 2016/05. 7.0. *Rules for the structure and drafting of International Standards*. http://www.iec.ch/members_experts/refdocs/iec/isoiecdir-2%7Bed7.0%7Den.pdf.

3 Definitions

For the purposes of this Standard the following definitions apply.

3.1 Display Definitions

| | |
|----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Characteristic Curve | <p>The inherent Display Function of a Display System including the effects of ambient light. The Characteristic Curve describes Luminance versus DDL of an emissive display device, such as a CRT/display controller system, or Luminance of light reflected from a print medium, or Luminance derived from the measured optical density versus DDL of a hard-copy medium and the given Luminance of a light-box. The Characteristic Curve depends on operating parameters of the Display System.</p> <p>Note</p> <p>The Luminance generated by an emissive display may be measured with a photometer. Diffuse optical density of a hard-copy may be measured with a densitometer.</p> |
| Contrast Sensitivity | characterizes the sensitivity of the average human observer to Luminance changes of the Standard Target. Contrast Sensitivity is inversely proportional to Threshold Modulation. |
| Contrast Threshold | A function that plots the Just-Noticeable Difference divided by the Luminance across the Luminance Range. |
| Digital Driving Level (DDL) | A digital value that given as input to a Display System produces a Luminance. The set of DDLs of a Display System is all the possible discrete values that can produce Luminance values on that Display System. The mapping of DDLs to Luminance values for a Display System produces the Characteristic Curve of that Display System. The actual output for a given DDL is specific to the Display System and is not corrected for the Grayscale Standard Display Function. |
| Display Function | A function that describes a defined grayscale rendition of a Display System, the mapping of the DDLs in a defined space to Luminance, including the effects of ambient light at a given state of adjustment of the Display System. Distinguished from Characteristic Curve, which is the inherent Display Function of a Display System. |
| Display System | A device or devices that accept DDLs to produce corresponding Luminance values. This includes emissive displays, transmissive hardcopy viewed on light boxes, and reflective hardcopy. |
| Illuminance | Light from the environment surrounding the Display System that illuminates the display medium. It contributes to the Luminance that is received by an observer from the image display. Ambient Light reduces the contrast in the image. |
| Just-Noticeable Difference (JND) | The Luminance difference of a given target under given viewing conditions that the average human observer can just perceive. |
| JND Index | The input value to the Grayscale Standard Display Function, such that one step in JND Index results in a Luminance difference that is a Just-Noticeable Difference. |
| Luminance | is the luminous intensity per unit area projected in a given direction. The International System unit (used in PS3.14) is candela per square meter (cd/m^2), which is sometimes called nit. Another unit often used is footlambert (fL). $1 \text{ fL} = 3.426 \text{ cd}/\text{m}^2$. |
| Luminance Range | The span of Luminance values of a Display System from a minimum Luminance to a maximum Luminance. |
| P-Value | A device independent value defined in a perceptually linear grayscale space. The output of the DICOM Presentation LUT is P-Values, i.e., the pixel value after all DICOM defined grayscale transformations have been applied. P-Values are the input to a Standardized Display System. |

| | |
|-------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Grayscale Standard Display Function | The mathematically defined mapping of an input JND index to Luminance values defined in PS3.14. |
| Standardized Display System | A device or devices that produce Luminance values that are related to input P-Values by the Grayscale Standard Display Function. How this is performed is not defined, though it may be achieved by transformation of P-Values into DDLs accepted by a Display System. |
| Standard Luminance Level | Any one of the Standard Luminance levels in Table B-1. |
| Standard Target | <p>A 2-deg x 2-deg square filled with a horizontal or vertical grating with sinusoidal modulation of 4 cycles per degree. The square is placed in a uniform background of a Luminance equal to the mean Luminance of the Target.</p> <p>Note</p> <p>The Standard Target is defined in terms of the subtended viewing angle, not in terms of the distance from the viewer to the target.</p> |
| Threshold Modulation | The minimum Luminance modulation required by the average human observer to detect the Standard Target at a given mean Luminance level. The Threshold Modulation corresponds to the Just-Noticeable Difference in Luminance of the Standard Target. |

4 Symbols and Abbreviations

The following symbols and abbreviations are used in PS3.14.

| | |
|------------------|-----------------------------------------------------------------------------------|
| ACR | American College of Radiology |
| ANSI | American National Standards Institute |
| CEN TC251 | Comite' Europeen de Normalisation - Technical Committee 251 - Medical Informatics |
| DICOM | Digital Imaging and Communications in Medicine |
| HL7 | Health Level 7 |
| IEEE | Institute of Electrical and Electronics Engineers |
| ISO | International Standards Organization |
| JIRA | Japan Medical Imaging and Radiological Systems Industries Association |
| NEMA | National Electrical Manufacturers Association |

5 Conventions

The following conventions are used in PS3.14:

The terminology defined in Section 3 above is capitalized throughout PS3.14.

6 Overview

PS3.14 defines, mathematically, the Grayscale Standard Display Function of Standardized Display Systems. These systems may be printers producing hard-copies viewed on light-boxes or electronic Display Systems for soft-copies.

Hard-copies may consist of transmissive films as well as reflective prints. The image in these prints is represented by optical density variations in transmission or diffuse reflection. To an observer, every element of the image appears with a certain Luminance depending on the Illuminance and the optical density of the image element.

Soft-copies may be produced by emissive Display Systems (such as CRT monitors) or electronic light valves (such as light sources and liquid crystal displays).

For the purpose of PS3.14, Display Systems take a Digital Driving Level and produce Luminance or optical density variations that represent the image. Predictable application of image transformations, such as the modality, value-of-interest, and presentation look-up tables specified in the DICOM standard, requires knowledge of the Characteristic Curve of the Display System. Standardizing the response function expected of the Display System simplifies the application of such image transformations across several different Display Systems such as encountered in a network environment.

PS3.14 does not define when conformance with the Grayscale Standard Display Function is achieved or how to characterize the degree of conformance reached.

Note

A definition of conformance would require thorough evaluations of human visual system sensitivity to deviations of Display Functions from the Grayscale Standard Display Function for medical images.

Figure 6-1 and Figure 6-2 show the context for the Grayscale Standard Display Function. The Grayscale Standard Display Function is part of the image presentation. There will be a number of other modifications to the image before the Grayscale Standard Display Function is applied. The image acquisition device will adjust the image as it is formed. Other elements may perform a "window and level" to select a part of the dynamic range of the image to be presented. Yet other elements can adjust the selected dynamic range in preparation for display. The Presentation LUT outputs P-Values (presentation values). These P-Values become the Digital Driving Levels for Standardized Display Systems. The Grayscale Standard Display Function maps P-Values to the log-luminance output of the Standardized Display System. How a Standardized Display System performs this mapping is implementation dependent.

The boundary between the DICOM model of the image acquisition and presentation chain, and the Standardized Display System, expressed in P-Values, is intended to be both device independent and conceptually (if not actually) perceptually linear. In other words, regardless of the capabilities of the Standardized Display System, the same range of P-Values will be presented isimilarly.



Figure 6-1. The Grayscale Standard Display Function is an element of the image presentation after several modifications to the image have been completed by other elements of the image acquisition and presentation chain.



Figure 6-2. The conceptual model of a Standardized Display System maps P-Values to Luminance via an intermediate transformation to Digital Driving Levels of an unstandardized Display System.

The main objective of PS3.14 is to define mathematically an appropriate Grayscale Standard Display Function for all image presentation systems. The purpose of defining this Grayscale Standard Display Function is to allow applications to know *a priori* how P-Values are transformed to viewed Luminance values by a Standardized Display System. In essence, defining the Grayscale Standard Display Function fixes the "units" for the P-Values output from the Presentation LUT and used as Digital Driving Levels to Standardized Display Systems.

A second objective of PS3.14 is to select a Display Function that provides some level of similarity in grayscale perception or basic appearance for a given image between Display Systems of different Luminance and that facilitates good use of the available Digital Driving Levels of a Display System. While many different functions could serve the primary objective, this Grayscale Standard Display Function was chosen to meet the second objective. With such a function, P-Values are approximately linearly related to human perceptual response. Similarity does not guarantee equal information content. Display Systems with a wider Luminance Range and/or higher Luminance will be capable of presenting more just-noticeable Luminance differences to an observer. Similarity also does not imply strict perceptual linearity, since perception is dependent on image content and on the viewer. In order to achieve strict perceptual linearity, applications would need to adjust the presentation of images to match user expectations through the other constructs defined in the DICOM Standard (e.g., VOI and Presentation LUT). Without a defined Display Function, such adjustments on the wide variety of Display Systems encountered on a network would be difficult.

The choice of the function is based on several ideas that are discussed further in Annex A.

Annex B contains the Grayscale Standard Display Function in tabular form.

Informative Annex C provides an example procedure for comparing mathematically the shape of the actual Display Function with the Grayscale Standard Display Function and for quantifying how well the actual discrete Luminance intervals match those of the Grayscale Standard Display Function.

Display Systems often will have Characteristic Curves different from the Grayscale Standard Display Function. These devices may contain means for incorporating externally defined transformations that make the devices conform with the Grayscale Standard Display Function. PS3.14 provides examples of test patterns for Display Systems with which their behavior can be measured and the approximation to the Grayscale Standard Display Function evaluated (see Informative Section D.1, Section D.2 and Section D.3).

7 The Grayscale Standard Display Function

As explained in greater detail in Annex A, the Grayscale Standard Display Function is based on human Contrast Sensitivity. Human Contrast Sensitivity is distinctly non-linear within the Luminance Range of the Grayscale Standard Display Function. The human eye is relatively less sensitive in the dark areas of an image than it is in the bright areas of an image. This variation in sensitivity makes it much easier to see small relative changes in Luminance in the bright areas of the image than in the dark areas of the image. A Display Function that adjusts the brightness such that equal changes in P-Values will result in the same level of perceptibility at all driving levels is "perceptually linearized". The Grayscale Standard Display Function incorporates the notion of perceptual linearization without making it an explicit objective of PS3.14.

The employed data for Contrast Sensitivity are derived from Barten's model of the human visual system (Ref. 1, 2 and Annex B). Specifically, the Grayscale Standard Display Function refers to Contrast Sensitivity for the Standard Target consisting of a 2-deg x 2-deg square filled with a horizontal or vertical grating with sinusoidal modulation of 4 cycles per degree. The square is placed in a uniform background of Luminance equal to the mean Luminance L of the Target. The Contrast Sensitivity is defined by the Threshold Modulation at which the grating becomes just visible to the average human observer. The Luminance modulation represents the Just-Noticeable Difference (JND) for the Target at the Luminance L .

Note

The academic nature of the Standard Target is recognized. With the simple target, the essential objectives of PS3.14 appear to be realizable. Only spurious results with more realistic targets in complex surroundings were known at the time of writing PS3.14 and these were not assessed.

The Grayscale Standard Display Function is defined for the Luminance Range from 0.05 to 4000 cd/m^2 . The minimum Luminance corresponds to the lowest practically useful Luminance of cathode-ray-tube (CRT) monitors and the maximum exceeds the unattenuated Luminance of very bright light-boxes used for interpreting X-Ray mammography. The Grayscale Standard Display Function explicitly includes the effects of the diffused ambient Illuminance.

Within the Luminance Range happen to fall 1023 JNDs (see Annex A).

7.1 General Formulas

The Grayscale Standard Display Function is defined by a mathematical interpolation of the 1023 Luminance levels derived from Barten's model. The Grayscale Standard Display Function allows us to calculate luminance, L , in candelas per square meter, as a function of the Just-Noticeable Difference (JND) Index, j :

$$\log_{10} L(j) = \frac{a + c \cdot \text{Ln}(j) + e \cdot (\text{Ln}(j))^2 + g \cdot (\text{Ln}(j))^3 + m \cdot (\text{Ln}(j))^4}{1 + b \cdot \text{Ln}(j) + d \cdot (\text{Ln}(j))^2 + f \cdot (\text{Ln}(j))^3 + h \cdot (\text{Ln}(j))^4 + k \cdot (\text{Ln}(j))^5} \quad (7-1)$$

with:

Ln referring to the natural logarithm

j the index (1 to 1023) of the Luminance levels L_j of the JNDs

$a = -1.3011877$

$b = -2.5840191\text{E-}2$

$c = 8.0242636\text{E-}2$

$d = -1.0320229\text{E-}1$

$e = 1.3646699\text{E-}1$

$f = 2.8745620\text{E-}2$

$g = -2.5468404\text{E-}2$

$h = -3.1978977\text{E-}3$

$$k = 1.2992634E-4$$

$$m = 1.3635334E-3$$

The logarithms to the base 10 of the Luminance L_j are very well interpolated by this function over the entire Luminance Range. The relative deviation of any $\log(\text{Luminance})$ -value from the function is at most 0.3%, and the root-mean-square-error is 0.0003. The continuous representation of the Grayscale Standard Display Function permits a user to compute discrete JNDs for arbitrary start levels and over any desired Luminance Range.

Note

1. To apply Equation 7-1 to a device with a specific range of L values, it is convenient to also have the inverse of this relationship, which is given by:

$$j(L) = A + B \cdot \text{Log}_{10}(L) + C \cdot (\text{Log}_{10}(L))^2 + D \cdot (\text{Log}_{10}(L))^3 + E \cdot (\text{Log}_{10}(L))^4 + F \cdot (\text{Log}_{10}(L))^5 + G \cdot (\text{Log}_{10}(L))^6 + H \cdot (\text{Log}_{10}(L))^7 + I \cdot (\text{Log}_{10}(L))^8 \quad (7-2)$$

where:

Log_{10} represents logarithm to the base 10

$$A = 71.498068$$

$$B = 94.593053$$

$$C = 41.912053$$

$$D = 9.8247004$$

$$E = 0.28175407$$

$$F = -1.1878455$$

$$G = -0.18014349$$

$$H = 0.14710899$$

$$I = -0.017046845$$

2. When incorporating the formulas for $L(j)$ and $j(L)$ into a computer program, the use of double precision is recommended.
3. Alternative methods may be used to calculate the JND Index values. One method is use a numerical algorithm such as the Van Vijnngaarden-Dekker-Brent method described in *Numerical Recipes in C* (Cambridge University press, 1991). The value j may be calculated from L iteratively given the Grayscale Standard Display Function's formula for $L(j)$. Another method would be to use the Grayscale Standard Display Function's tabulated values of j and L to calculate the j corresponding to an arbitrary L by linearly interpolating between the two nearest tabulated L, j pairs.
4. No specification is intended as to how these formulas are implemented. These could be implemented dynamically, by executing the equation directly, or through discrete values, such as a LUT, etc.

Annex B lists the Luminance levels computed with this equation for the 1023 integer JND Indices and Figure 7-1 shows a plot of the Grayscale Standard Display Function. The exact value of the Luminance levels, of course, depends on the start level of 0.05 cd/m^2 .

The Characteristic Curve of a Display System represents the Luminance produced by a Display System as a function of DDL and the effect of ambient Illuminance. The Characteristic Curve is measured with Standard Test Patterns (see Annex D). In general, the Display Function describes, for example,

- a. the Luminance (including ambient Illuminance) measured as a function of DDL for emissive displays such as a CRT-monitor/digital display controller system,
- b. the Luminance (including ambient Illuminance) as a function of DDL measured for a transmissive medium hung in front of a light-box after a printer produced an optical density, depending on DDL, on the medium,

- c. the Luminance (including ambient light) as a function of DDL measured for a diffusely reflective medium illuminated by a office lights after a printer produced a reflective density, depending on DDL, on the medium.

By internal or external means, the system may have been configured (or calibrated) such that the Characteristic Curve is consistent with the Grayscale Standard Display Function.

Some Display Systems adapt themselves to ambient light conditions. Such a system may conform to the Grayscale Standard Display Function for one level of ambient Illuminance only, unless it had the capability of adjusting its Display Function without user-intervention so that it remains in conformance with the Grayscale Standard Display Function.

7.2 Transmissive Hardcopy Printers

For transmissive hardcopy printing, the relationship between luminance, L , and the printed optical density, D , is:

$$L = L_a + L_0 \cdot 10^{-D} \quad (7-3)$$

where:

L_0 is the luminance of the light box with no film present

L_a is the luminance contribution due to ambient illuminance reflected off the film

If film is to be printed with a density ranging from D_{\min} to D_{\max} , the final luminance will range between $L_{\min} = L_a + L_0 \cdot 10^{-D_{\max}}$ and $L_{\max} = L_a + L_0 \cdot 10^{-D_{\min}}$ and the j values will correspondingly range from $j_{\min} = j(L_{\min})$ to $j_{\max} = j(L_{\max})$.

If this span of j values is represented by an N -bit P-Value, ranging from 0 for j_{\min} to $2N-1$ for j_{\max} , the j values will correspond to P-Values as follows:

$$j(p) = j_{\min} + \frac{p}{2^N - 1} \cdot (j_{\max} - j_{\min}) \quad (7-4)$$

and the corresponding L values will be $L(j(p))$.

Finally, converting the $L(j(p))$ values to densities results in:

$$D(p) = -\log_{10} \left(\frac{L(j(p)) - L_a}{L_0} \right) \quad (7-5)$$

Note

Typical values for the parameters used in transmissive hardcopy printing are $L_0 = 2000 \text{ cd/m}^2$, $L_a = 10 \text{ cd/m}^2$.

7.3 Reflective Hardcopy Printers

For reflective hardcopy printing, the relationship between luminance, L , and the printed optical density, D , is:

$$L = L_0 \cdot 10^{-D} \quad (7-6)$$

where:

L_0 is the maximum luminance obtainable from diffuse reflection of the illumination that is present.

If film is to be printed with a density ranging from D_{\min} to D_{\max} , the final luminance will range between $L_{\min} = L_0 \cdot 10^{-D_{\max}}$ and $L_{\max} = L_0 \cdot 10^{-D_{\min}}$ and the j values will correspondingly range from $j_{\min} = j(L_{\min})$ to $j_{\max} = j(L_{\max})$.

If this span of j values is represented by an N -bit P -Value, ranging from 0 for j_{\min} to $2N-1$ for j_{\max} , the j values will correspond to P -Values as follows:

$$j(p) = j_{\min} + \frac{p}{2^N - 1} \cdot (j_{\max} - j_{\min}) \quad (7-7)$$

and the corresponding L values will be $L(j(p))$.

Finally, converting the $L(j(p))$ values to densities results in

$$D(p) = -\log_{10} \left(\frac{L(j(p))}{L_0} \right) \quad (7-8)$$

Note

Typical values for the parameters used in reflective hardcopy printing are $L_0 = 150 \text{ cd/m}^2$.

8 References

- 1) Barten, P.G.J., Physical model for the Contrast Sensitivity of the human eye. Proc. SPIE 1666, 57-72 (1992)
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Figure 7-1. The Grayscale Standard Display Function presented as logarithm-of-Luminance versus JND-Index

A Derivation of the Grayscale Standard Display Function (Informative)

A.1 Rationale For Selecting the Grayscale Standard Display Function

In choosing the Grayscale Standard Display Function, it was considered mandatory to have only one continuous, monotonically behaving mathematical function for the entire Luminance Range of interest. Correspondingly, for simplicity of implementing the Grayscale Standard Display Function, it was felt to be useful to define it by only one table of data pairs. As a secondary objective, it was considered desirable that the Grayscale Standard Display Function provide similarity in grayscale rendition on Display Systems of different Luminance Range and that good use of the available DDLs of a Display System was facilitated.

Perceptual linearization was thought to be a useful concept for arriving at a Grayscale Standard Display Function for meeting the above secondary objectives; however, it is not considered an objective by itself. Apart from the fact that is probably an elusive goal to perceptually linearize all types of medical images under various viewing conditions by one mathematical function, medical images are mostly presented by application-specific Display Functions that assign contrast non-uniformly according to clinical needs.

Intuitively, one would assume that perceptually linearized images on different Display Systems will be judged to be similar. To achieve perceptual linearization, a model of the human visual system response was required and the Barten model [A1] was chosen.

Early experiments showed that an appealing degree of contrast equalization and similarity could be obtained with a Display Function derived from Barten's model of human visual system response. The employed images were square patterns, the SMPTE pattern, and the Briggs' pattern [A2].

It was wished to relate DDLs of a Display System to some perceptually linear scale, primarily, to gain efficient utilization of the available input levels. If digitization levels lead to luminance or optical density levels that are perceptually indistinguishable, they are wasted. If they are too far apart, the observer may see contours. Hence, the concept of perceptual linearization was retained, not as a goal for the Grayscale Standard Display Function, but to obtain a concept for a measure of how well these objectives have been met.

Perceptual linearization is realizable, in a strict sense, only for rather simple images like square patterns or gratings in a uniform surrounding. Nevertheless, the concept of a perceptually linearized Display Function derived from experiments with simple test patterns has been successfully applied to complex images as described in the literature [A3-A8]. While it was clearly recognized that perceptual linearization can never be achieved for all details or spatial frequencies and object sizes at once, perceptual linearization for frequencies and object sizes near the peak of human Contrast Sensitivity seemed to do a reasonable job also in complex images.

Limited (unpublished) experiments have indicated that perceptual linearization for a particular detail in a complex image with a wide Luminance Range and heterogeneous surround required Display Functions that are rather strongly bent in the dark regions of the image and that such Display Functions for a low-luminance and a high-luminance display system would not be part of a continuous, monotonic function. This experience may underlie the considerations of the CIE Lab curve [A9] proposed by other standards groups.

Other experiments and observations with computed radiographs seemed to suggest that similarity could also be obtained between grayscale renditions on Display Systems of different Luminance when the same application-specific function is combined with log-linear Characteristic Curves of the Display Systems. Thus similarity, if not contrast equalization, could be gained by a straight, luminance-independent shape for the Display Function.

While it might have been equally sensible to choose the rather simple log-linear Display Function as a standard, this was not done for the following reason, among others.

For high-resolution Display Systems with high intrinsic video bandwidth, digitization resolution is limited to 8 or 10 bits because of technology and other constraints. The more a Grayscale Standard Display Function deviates from the Characteristic Curve of a Display System, the poorer the utilization of DDLs typically is from a perception point of view. The Characteristic Curve of CRT Display Systems has a convex curvature with respect to a log-linear straight line. It differs much less from Display Functions derived from human vision models and the concept of perceptual linearization than from a log-linear Display Function.

When using application-specific display processes that cause the resultant Display Function to deviate strongly from the Grayscale Standard Display Function, the function conceivably does not provide good similarity. In this case, other functions may yield better similarity.

In summary, a Display Function was derived from Barten's model of the human visual system to gain a single continuous mathematical function which in its curvature falls between a log-linear response and a Display Function that may yield perceptual linearization in complex scenery with a wide luminance range within the image. Other models of human contrast sensitivity may potentially provide a better function, but were not evaluated. The notion of perceptual linearization was chosen to meet the secondary objectives of the Grayscale Standard Display Function, but not as an explicit goal of the Grayscale Standard Display Function itself. It is recognized that better functions may exist to meet these objectives. It is believed that almost any single mathematically defined Standard Function will greatly improve image presentations on Display Systems in communication networks.

A.2 Details of the Barten Model

Barten's model considers neural noise, lateral inhibition, photon noise, external noise, limited integration capability, the optical modulation transfer function, orientation, and temporal filtering. Neuron noise represents the upper limit of Contrast Sensitivity at high spatial frequencies. Low spatial frequencies appear to be attenuated by lateral inhibition in the ganglion cells that seems to be caused by the subtraction of a spatially low-pass filtered signal from the original. Photon noise is defined by the fluctuations of the photon flux h , the pupil diameter d , and quantum detection efficiency η of the eye. At low light levels, the Contrast Sensitivity is proportional to the square-root of Luminance according to the de Vries-Rose law. The temporal integration capability in the model used here is simply represented by a time constant of $T = 0.1$ sec. Temporal filtering effects are not included. Next to the temporal integration capability, the eye also has limited spatial integration capability: There is a maximum angular size $X_E \times Y_E$ as well as a maximum number of cycles N_E over which the eye can integrate information in the presence of various noise sources. The optical modulation transfer function

$$M_{\text{opt}}(u) = e^{-\pi^2 \cdot \sigma^2 \cdot u^2} \quad \sigma = \sqrt{\sigma_0^2 + (C_{\text{sph}} \cdot d^3)^2} \quad (\text{A-1})$$

(u , spatial frequency in c/deg) is derived from a Gaussian point-spread function including the optical properties of the eye-lens, stray light from the optical media, diffusion in the retina, and the discrete nature of the receptor elements as well as from the spherical aberration, C_{sph} , which is the main pupil-diameter-dependent component. σ_0 is the value of σ at small pupil sizes. External noise may stem from Display System noise and image noise. Contrast sensitivity varies approximately sinusoidally with the orientation of the test pattern with equal maximum sensitivity at 0 and 90 deg and minimal sensitivity at 45 de.g., The difference in Contrast Sensitivity is only present at high spatial frequencies. The effect is modeled by a variation in integration capability.

The combination of these effects yields the equation for contrast as a function of spatial frequency:

$$S(u) = \frac{1}{k} \sqrt{\frac{T}{2}} \frac{M_{\text{opt}}(u)}{\sqrt{\left(\frac{1}{\eta h L} + \frac{\Phi_0}{(1-F(u))^2} + \Phi_{\text{ext}}(u) \right) \cdot \left(\frac{1}{X_0^2} + \frac{1}{X_E^2} + \left(\frac{u}{N_E} \right)^2 \right)}} \quad (\text{A-2})$$

The effect of noise appears in the first parenthesis within the square-root as a noise contrast related to the variances of photon (first term), filtered neuron (second term), and external noise. The Illuminance, $I_L = \pi/4 \cdot d^2 \cdot L$, of the eye is expressed in trolands [td], d is the pupil diameter in mm, and L the Luminance of the Target in cd/m^2 . The pupil diameter is determined by the formula of de Groot and Gebhard:

$$d = 4.6 - 2.8 \cdot \tanh(0.4 \cdot \log_{10}(0.625 \cdot L)) \quad (\text{A-3})$$

The term $(1 - F(u))^2 = 1 - \exp(-u^2/u_0^2)$ describes the low frequency attenuation of neuron noise due to lateral inhibition ($u_0 = 8$ c/deg). Equation A-2 represents the simplified case of square targets, $X_0 = Y_0$ [deg]. Φ_{ext} is the contrast variance corresponding to external noise. $k = 3.3$, $\eta = 0.025$, $h = 357.3600$ photons/td sec deg^2 ; the contrast variance corresponding to the neuron noise $\Phi_0 = 3 \cdot 10^{-8}$ sec deg^2 , $X_E = 12$ deg, $N_E = 15$ cycles (at 0 and 90 deg and $N_E = 7.5$ cycles at 45 deg for frequencies above 2 c/deg), $\sigma_0 = 0.0133$ deg, $C_{\text{sph}} = 0.0001 \text{ deg/mm}^3$ [A1]. Equation A-2 provides a good fit of experimental data for $10^{-4} \leq L \leq 103 \text{ cd/m}^2$, $0.5 \leq X_0 \leq 60$ deg, $0.2 \leq u \leq 50$ c/deg.

After inserting all constants, Equation A-2 reduces to

$$S(L) = \frac{q_1 \cdot M_{opt}(L)}{\sqrt{\frac{q_2}{d^2 L} + q_3}} \quad (A-4)$$

with $q_1 = 0.1183034375$, $q_2 = 3.962774805 \cdot 10^{-5}$, and $q_3 = 1.356243499 \cdot 10^{-7}$.

When viewed from 250 mm distance, the Standard Target has a size of about 8.7 mm x 8.7 mm and the spatial frequency of the grid equals about 0.92 line pairs per millimeter.

The Grayscale Standard Display Function is obtained by computing the Threshold Modulation S_j as a function of mean grating Luminance and then stacking these values on top of each other. The mean Luminance of the next higher level is calculated by adding the peak-to-peak modulation to the mean Luminance L_j of the previous level:

$$L_{j+1} = L_j \cdot \frac{1 + S_j}{1 - S_j} \quad (A-5)$$

Thus, in PS3.14, the peak-to-peak Threshold Modulation is called a just-noticeable Luminance difference.

When a Display System conforms with the Grayscale Standard Display Function, it is perceptually linearized when observing the Standard Target: If a Display System had infinitely fine digitization resolution, equal increments in P-Value would produce equally perceivable contrast steps and, under certain conditions, just-noticeable Luminance differences (displayed one at a time) for the Standard Target (the grating with sinusoidal modulation of 4 c/degree over a 2 degree x 2 degree area, embedded in a uniform background with a Luminance equal to the mean target Luminance).

The display of the Standard Target at different Luminance levels one at a time is an academic display situation. An image containing different Luminance levels with different targets and Luminance distributions at the same time is in general not perceptually linearized. It is once more emphasized that the concept of perceptual linearization of Display Systems for the Standard Target served as a logical means for deriving a continuous mathematical function and for meeting the secondary goals of the Grayscale Standard Display Function. The function may represent a compromise between perceptual linearization of complex images by strongly-bent Display Functions and gaining similarity of grayscale perception within an image on Display Systems of different Luminance by a log-linear Display Function.

The Characteristic Curve of the Display System is measured and represented by {Luminance, DDL}-pairs $L_m = F(D_m)$. A discrete transformation may be performed that maps the previously used DDLs, D_{input} , to D_{output} according to Equations (A6) and (A7) such that the available ensemble of discrete Luminance levels is used to approximate the Grayscale Standard Display Function $L = G(j)$. The transformation is illustrated in Fig. A1. By such an operation, conformance with the Grayscale Standard Display Function may be reached.

$$D_{output} = s \cdot F^{-1}[G(j)] \quad (A-6)$$

s is a scale factor for accommodating different input and output digitization resolutions.

The index j (which in general will be a non-integer number) of the Standard Luminance Levels is determined from the starting index j_0 of the Standard Luminance level at the minimum Luminance of the Display System (including ambient light), the number of Standard JNDs, N_{JND} , over the Luminance Range of the Display System, the digitization resolution DR , and the DDLs, D_{input} , of the Display System:

$$j = j_0 + N_{JND} / DR \cdot D_{input} \quad (A-7)$$

A detailed example for executing such a transformation is given in Annex D.

A.3 References

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[A9] CIE 1976

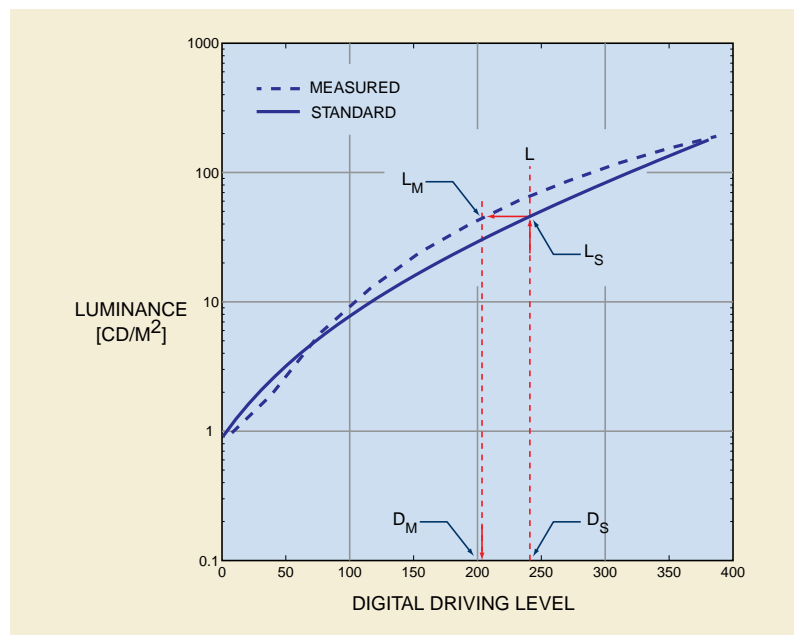


Figure A-1. Illustration for determining the transform that changes the Characteristic Curve of a Display System to a Display Function that approximates the Grayscale Standard Display Function

B Table of the Grayscale Standard Display Function (Informative)

The Grayscale Standard Display Function based on the Barten model was introduced in Section 7 and details are presented in Annex A above. This annex presents the Grayscale Standard Display Function as a table of values for Luminance as a function of the Just-Noticeable Difference Index for integer values of the Just-Noticeable Difference Index.

Table B-1. Grayscale Standard Display Function: Luminance versus JND Index

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|-----|-----------------------|-----|-----------------------|-----|-----------------------|-----|-----------------------|
| 1 | 0.0500 | 2 | 0.0547 | 3 | 0.0594 | 4 | 0.0643 |
| 5 | 0.0696 | 6 | 0.0750 | 7 | 0.0807 | 8 | 0.0866 |
| 9 | 0.0927 | 10 | 0.0991 | 11 | 0.1056 | 12 | 0.1124 |
| 13 | 0.1194 | 14 | 0.1267 | 15 | 0.1342 | 16 | 0.1419 |
| 17 | 0.1498 | 18 | 0.1580 | 19 | 0.1664 | 20 | 0.1750 |
| 21 | 0.1839 | 22 | 0.1931 | 23 | 0.2025 | 24 | 0.2121 |
| 25 | 0.2220 | 26 | 0.2321 | 27 | 0.2425 | 28 | 0.2532 |
| 29 | 0.2641 | 30 | 0.2752 | 31 | 0.2867 | 32 | 0.2984 |
| 33 | 0.3104 | 34 | 0.3226 | 35 | 0.3351 | 36 | 0.3479 |
| 37 | 0.3610 | 38 | 0.3744 | 39 | 0.3880 | 40 | 0.4019 |
| 41 | 0.4161 | 42 | 0.4306 | 43 | 0.4454 | 44 | 0.4605 |
| 45 | 0.4759 | 46 | 0.4916 | 47 | 0.5076 | 48 | 0.5239 |
| 49 | 0.5405 | 50 | 0.5574 | 51 | 0.5746 | 52 | 0.5921 |
| 53 | 0.6100 | 54 | 0.6281 | 55 | 0.6466 | 56 | 0.6654 |
| 57 | 0.6846 | 58 | 0.7040 | 59 | 0.7238 | 60 | 0.7440 |
| 61 | 0.7644 | 62 | 0.7852 | 63 | 0.8064 | 64 | 0.8278 |
| 65 | 0.8497 | 66 | 0.8718 | 67 | 0.8944 | 68 | 0.9172 |
| 69 | 0.9405 | 70 | 0.9640 | 71 | 0.9880 | 72 | 1.0123 |
| 73 | 1.0370 | 74 | 1.0620 | 75 | 1.0874 | 76 | 1.1132 |
| 77 | 1.1394 | 78 | 1.1659 | 79 | 1.1928 | 80 | 1.2201 |
| 81 | 1.2478 | 82 | 1.2759 | 83 | 1.3044 | 84 | 1.3332 |
| 85 | 1.3625 | 86 | 1.3921 | 87 | 1.4222 | 88 | 1.4527 |
| 89 | 1.4835 | 90 | 1.5148 | 91 | 1.5465 | 92 | 1.5786 |
| 93 | 1.6111 | 94 | 1.6441 | 95 | 1.6775 | 96 | 1.7113 |
| 97 | 1.7455 | 98 | 1.7802 | 99 | 1.8153 | 100 | 1.8508 |
| 101 | 1.8868 | 102 | 1.9233 | 103 | 1.9601 | 104 | 1.9975 |
| 105 | 2.0352 | 106 | 2.0735 | 107 | 2.1122 | 108 | 2.1514 |
| 109 | 2.1910 | 110 | 2.2311 | 111 | 2.2717 | 112 | 2.3127 |
| 113 | 2.3543 | 114 | 2.3963 | 115 | 2.4388 | 116 | 2.4817 |
| 117 | 2.5252 | 118 | 2.5692 | 119 | 2.6137 | 120 | 2.6587 |
| 121 | 2.7041 | 122 | 2.7501 | 123 | 2.7966 | 124 | 2.8436 |
| 125 | 2.8912 | 126 | 2.9392 | 127 | 2.9878 | 128 | 3.0369 |
| 129 | 3.0866 | 130 | 3.1367 | 131 | 3.1875 | 132 | 3.2387 |

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|-----|-----------------------|-----|-----------------------|-----|-----------------------|-----|-----------------------|
| 133 | 3.2905 | 134 | 3.3429 | 135 | 3.3958 | 136 | 3.4493 |
| 137 | 3.5033 | 138 | 3.5579 | 139 | 3.6131 | 140 | 3.6688 |
| 141 | 3.7252 | 142 | 3.7820 | 143 | 3.8395 | 144 | 3.8976 |
| 145 | 3.9563 | 146 | 4.0155 | 147 | 4.0754 | 148 | 4.1358 |
| 149 | 4.1969 | 150 | 4.2586 | 151 | 4.3209 | 152 | 4.3838 |
| 153 | 4.4473 | 154 | 4.5115 | 155 | 4.5763 | 156 | 4.6417 |
| 157 | 4.7078 | 158 | 4.7745 | 159 | 4.8419 | 160 | 4.9099 |
| 161 | 4.9785 | 162 | 5.0479 | 163 | 5.1179 | 164 | 5.1886 |
| 165 | 5.2599 | 166 | 5.3319 | 167 | 5.4046 | 168 | 5.4780 |
| 169 | 5.5521 | 170 | 5.6269 | 171 | 5.7024 | 172 | 5.7786 |
| 173 | 5.8555 | 174 | 5.9331 | 175 | 6.0114 | 176 | 6.0905 |
| 177 | 6.1702 | 178 | 6.2508 | 179 | 6.3320 | 180 | 6.4140 |
| 181 | 6.4968 | 182 | 6.5803 | 183 | 6.6645 | 184 | 6.7496 |
| 185 | 6.8354 | 186 | 6.9219 | 187 | 7.0093 | 188 | 7.0974 |
| 189 | 7.1863 | 190 | 7.2760 | 191 | 7.3665 | 192 | 7.4578 |
| 193 | 7.5500 | 194 | 7.6429 | 195 | 7.7366 | 196 | 7.8312 |
| 197 | 7.9266 | 198 | 8.0229 | 199 | 8.1199 | 200 | 8.2179 |
| 201 | 8.3167 | 202 | 8.4163 | 203 | 8.5168 | 204 | 8.6182 |
| 205 | 8.7204 | 206 | 8.8235 | 207 | 8.9275 | 208 | 9.0324 |
| 209 | 9.1382 | 210 | 9.2449 | 211 | 9.3525 | 212 | 9.4611 |
| 213 | 9.5705 | 214 | 9.6809 | 215 | 9.7922 | 216 | 9.9044 |
| 217 | 10.0176 | 218 | 10.1318 | 219 | 10.2469 | 220 | 10.3629 |
| 221 | 10.4800 | 222 | 10.5980 | 223 | 10.7169 | 224 | 10.8369 |
| 225 | 10.9579 | 226 | 11.0799 | 227 | 11.2028 | 228 | 11.3268 |
| 229 | 11.4518 | 230 | 11.5779 | 231 | 11.7050 | 232 | 11.8331 |
| 233 | 11.9622 | 234 | 12.0925 | 235 | 12.2237 | 236 | 12.3561 |
| 237 | 12.4895 | 238 | 12.6240 | 239 | 12.7596 | 240 | 12.8963 |
| 241 | 13.0341 | 242 | 13.1730 | 243 | 13.3130 | 244 | 13.4542 |
| 245 | 13.5965 | 246 | 13.7399 | 247 | 13.8844 | 248 | 14.0302 |
| 249 | 14.1770 | 250 | 14.3251 | 251 | 14.4743 | 252 | 14.6247 |
| 253 | 14.7763 | 254 | 14.9291 | 255 | 15.0831 | 256 | 15.2384 |
| 257 | 15.3948 | 258 | 15.5525 | 259 | 15.7114 | 260 | 15.8716 |
| 261 | 16.0330 | 262 | 16.1957 | 263 | 16.3596 | 264 | 16.5249 |
| 265 | 16.6914 | 266 | 16.8592 | 267 | 17.0283 | 268 | 17.1987 |
| 269 | 17.3705 | 270 | 17.5436 | 271 | 17.7180 | 272 | 17.8938 |
| 273 | 18.0709 | 274 | 18.2494 | 275 | 18.4293 | 276 | 18.6105 |
| 277 | 18.7931 | 278 | 18.9772 | 279 | 19.1626 | 280 | 19.3495 |
| 281 | 19.5378 | 282 | 19.7275 | 283 | 19.9187 | 284 | 20.1113 |
| 285 | 20.3054 | 286 | 20.5009 | 287 | 20.6980 | 288 | 20.8965 |
| 289 | 21.0966 | 290 | 21.2981 | 291 | 21.5012 | 292 | 21.7058 |
| 293 | 21.9120 | 294 | 22.1197 | 295 | 22.3289 | 296 | 22.5398 |
| 297 | 22.7522 | 298 | 22.9662 | 299 | 23.1818 | 300 | 23.3990 |

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|-----|-----------------------|-----|-----------------------|-----|-----------------------|-----|-----------------------|
| 301 | 23.6179 | 302 | 23.8383 | 303 | 24.0605 | 304 | 24.2842 |
| 305 | 24.5097 | 306 | 24.7368 | 307 | 24.9656 | 308 | 25.1961 |
| 309 | 25.4283 | 310 | 25.6622 | 311 | 25.8979 | 312 | 26.1353 |
| 313 | 26.3744 | 314 | 26.6153 | 315 | 26.8580 | 316 | 27.1025 |
| 317 | 27.3488 | 318 | 27.5969 | 319 | 27.8468 | 320 | 28.0985 |
| 321 | 28.3521 | 322 | 28.6075 | 323 | 28.8648 | 324 | 29.1240 |
| 325 | 29.3851 | 326 | 29.6481 | 327 | 29.9130 | 328 | 30.1798 |
| 329 | 30.4486 | 330 | 30.7193 | 331 | 30.9920 | 332 | 31.2667 |
| 333 | 31.5434 | 334 | 31.8220 | 335 | 32.1027 | 336 | 32.3854 |
| 337 | 32.6702 | 338 | 32.9570 | 339 | 33.2459 | 340 | 33.5369 |
| 341 | 33.8300 | 342 | 34.1251 | 343 | 34.4224 | 344 | 34.7219 |
| 345 | 35.0235 | 346 | 35.3272 | 347 | 35.6332 | 348 | 35.9413 |
| 349 | 36.2516 | 350 | 36.5642 | 351 | 36.8790 | 352 | 37.1960 |
| 353 | 37.5153 | 354 | 37.8369 | 355 | 38.1608 | 356 | 38.4870 |
| 357 | 38.8155 | 358 | 39.1463 | 359 | 39.4795 | 360 | 39.8151 |
| 361 | 40.1530 | 362 | 40.4933 | 363 | 40.8361 | 364 | 41.1813 |
| 365 | 41.5289 | 366 | 41.8790 | 367 | 42.2316 | 368 | 42.5866 |
| 369 | 42.9442 | 370 | 43.3043 | 371 | 43.6669 | 372 | 44.0321 |
| 373 | 44.3998 | 374 | 44.7702 | 375 | 45.1431 | 376 | 45.5187 |
| 377 | 45.8969 | 378 | 46.2778 | 379 | 46.6613 | 380 | 47.0475 |
| 381 | 47.4365 | 382 | 47.8281 | 383 | 48.2225 | 384 | 48.6197 |
| 385 | 49.0196 | 386 | 49.4224 | 387 | 49.8279 | 388 | 50.2363 |
| 389 | 50.6475 | 390 | 51.0616 | 391 | 51.4786 | 392 | 51.8985 |
| 393 | 52.3213 | 394 | 52.7470 | 395 | 53.1757 | 396 | 53.6074 |
| 397 | 54.0421 | 398 | 54.4798 | 399 | 54.9205 | 400 | 55.3643 |
| 401 | 55.8112 | 402 | 56.2611 | 403 | 56.7142 | 404 | 57.1704 |
| 405 | 57.6298 | 406 | 58.0923 | 407 | 58.5581 | 408 | 59.0270 |
| 409 | 59.4992 | 410 | 59.9747 | 411 | 60.4534 | 412 | 60.9354 |
| 413 | 61.4208 | 414 | 61.9094 | 415 | 62.4015 | 416 | 62.8969 |
| 417 | 63.3958 | 418 | 63.8980 | 419 | 64.4037 | 420 | 64.9129 |
| 421 | 65.4256 | 422 | 65.9418 | 423 | 66.4615 | 424 | 66.9848 |
| 425 | 67.5117 | 426 | 68.0422 | 427 | 68.5763 | 428 | 69.1140 |
| 429 | 69.6555 | 430 | 70.2006 | 431 | 70.7495 | 432 | 71.3021 |
| 433 | 71.8585 | 434 | 72.4187 | 435 | 72.9827 | 436 | 73.5505 |
| 437 | 74.1222 | 438 | 74.6978 | 439 | 75.2773 | 440 | 75.8608 |
| 441 | 76.4482 | 442 | 77.0396 | 443 | 77.6351 | 444 | 78.2346 |
| 445 | 78.8381 | 446 | 79.4458 | 447 | 80.0576 | 448 | 80.6735 |
| 449 | 81.2936 | 450 | 81.9179 | 451 | 82.5464 | 452 | 83.1792 |
| 453 | 83.8163 | 454 | 84.4577 | 455 | 85.1034 | 456 | 85.7535 |
| 457 | 86.4079 | 458 | 87.0668 | 459 | 87.7302 | 460 | 88.3980 |
| 461 | 89.0703 | 462 | 89.7472 | 463 | 90.4286 | 464 | 91.1147 |
| 465 | 91.8053 | 466 | 92.5006 | 467 | 93.2006 | 468 | 93.9053 |

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|-----|-----------------------|-----|-----------------------|-----|-----------------------|-----|-----------------------|
| 469 | 94.6147 | 470 | 95.3289 | 471 | 96.0480 | 472 | 96.7718 |
| 473 | 97.5005 | 474 | 98.2341 | 475 | 98.9726 | 476 | 99.7161 |
| 477 | 100.4646 | 478 | 101.2181 | 479 | 101.9767 | 480 | 102.7403 |
| 481 | 103.5091 | 482 | 104.2830 | 483 | 105.0621 | 484 | 105.8464 |
| 485 | 106.6359 | 486 | 107.4308 | 487 | 108.2309 | 488 | 109.0364 |
| 489 | 109.8473 | 490 | 110.6637 | 491 | 111.4854 | 492 | 112.3127 |
| 493 | 113.1455 | 494 | 113.9838 | 495 | 114.8278 | 496 | 115.6773 |
| 497 | 116.5326 | 498 | 117.3935 | 499 | 118.2602 | 500 | 119.1326 |
| 501 | 120.0109 | 502 | 120.8950 | 503 | 121.7850 | 504 | 122.6809 |
| 505 | 123.5828 | 506 | 124.4907 | 507 | 125.4047 | 508 | 126.3247 |
| 509 | 127.2508 | 510 | 128.1831 | 511 | 129.1215 | 512 | 130.0662 |
| 513 | 131.0172 | 514 | 131.9745 | 515 | 132.9381 | 516 | 133.9082 |
| 517 | 134.8847 | 518 | 135.8676 | 519 | 136.8571 | 520 | 137.8531 |
| 521 | 138.8557 | 522 | 139.8650 | 523 | 140.8810 | 524 | 141.9037 |
| 525 | 142.9331 | 526 | 143.9694 | 527 | 145.0125 | 528 | 146.0625 |
| 529 | 147.1195 | 530 | 148.1835 | 531 | 149.2545 | 532 | 150.3326 |
| 533 | 151.4178 | 534 | 152.5101 | 535 | 153.6097 | 536 | 154.7166 |
| 537 | 155.8307 | 538 | 156.9523 | 539 | 158.0812 | 540 | 159.2175 |
| 541 | 160.3614 | 542 | 161.5128 | 543 | 162.6718 | 544 | 163.8384 |
| 545 | 165.0128 | 546 | 166.1948 | 547 | 167.3847 | 548 | 168.5824 |
| 549 | 169.7880 | 550 | 171.0015 | 551 | 172.2230 | 552 | 173.4526 |
| 553 | 174.6902 | 554 | 175.9360 | 555 | 177.1900 | 556 | 178.4522 |
| 557 | 179.7227 | 558 | 181.0016 | 559 | 182.2889 | 560 | 183.5846 |
| 561 | 184.8889 | 562 | 186.2017 | 563 | 187.5232 | 564 | 188.8533 |
| 565 | 190.1921 | 566 | 191.5398 | 567 | 192.8963 | 568 | 194.2617 |
| 569 | 195.6360 | 570 | 197.0194 | 571 | 198.4119 | 572 | 199.8134 |
| 573 | 201.2242 | 574 | 202.6442 | 575 | 204.0735 | 576 | 205.5122 |
| 577 | 206.9603 | 578 | 208.4179 | 579 | 209.8851 | 580 | 211.3618 |
| 581 | 212.8482 | 582 | 214.3444 | 583 | 215.8503 | 584 | 217.3661 |
| 585 | 218.8919 | 586 | 220.4276 | 587 | 221.9733 | 588 | 223.5292 |
| 589 | 225.0952 | 590 | 226.6715 | 591 | 228.2581 | 592 | 229.8550 |
| 593 | 231.4624 | 594 | 233.0803 | 595 | 234.7088 | 596 | 236.3479 |
| 597 | 237.9977 | 598 | 239.6583 | 599 | 241.3297 | 600 | 243.0120 |
| 601 | 244.7054 | 602 | 246.4097 | 603 | 248.1252 | 604 | 249.8519 |
| 605 | 251.5899 | 606 | 253.3392 | 607 | 255.0999 | 608 | 256.8721 |
| 609 | 258.6559 | 610 | 260.4512 | 611 | 262.2583 | 612 | 264.0772 |
| 613 | 265.9079 | 614 | 267.7506 | 615 | 269.6052 | 616 | 271.4720 |
| 617 | 273.3509 | 618 | 275.2420 | 619 | 277.1455 | 620 | 279.0614 |
| 621 | 280.9897 | 622 | 282.9306 | 623 | 284.8841 | 624 | 286.8504 |
| 625 | 288.8294 | 626 | 290.8213 | 627 | 292.8262 | 628 | 294.8442 |
| 629 | 296.8752 | 630 | 298.9195 | 631 | 300.9770 | 632 | 303.0480 |
| 633 | 305.1324 | 634 | 307.2304 | 635 | 309.3420 | 636 | 311.4673 |

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|-----|-----------------------|-----|-----------------------|-----|-----------------------|-----|-----------------------|
| 637 | 313.6065 | 638 | 315.7595 | 639 | 317.9266 | 640 | 320.1077 |
| 641 | 322.3030 | 642 | 324.5126 | 643 | 326.7365 | 644 | 328.9749 |
| 645 | 331.2278 | 646 | 333.4953 | 647 | 335.7776 | 648 | 338.0747 |
| 649 | 340.3867 | 650 | 342.7137 | 651 | 345.0558 | 652 | 347.4131 |
| 653 | 349.7858 | 654 | 352.1738 | 655 | 354.5773 | 656 | 356.9964 |
| 657 | 359.4312 | 658 | 361.8818 | 659 | 364.3483 | 660 | 366.8308 |
| 661 | 369.3294 | 662 | 371.8442 | 663 | 374.3754 | 664 | 376.9229 |
| 665 | 379.4869 | 666 | 382.0676 | 667 | 384.6650 | 668 | 387.2793 |
| 669 | 389.9105 | 670 | 392.5587 | 671 | 395.2241 | 672 | 397.9068 |
| 673 | 400.6069 | 674 | 403.3245 | 675 | 406.0596 | 676 | 408.8125 |
| 677 | 411.5833 | 678 | 414.3719 | 679 | 417.1787 | 680 | 420.0036 |
| 681 | 422.8468 | 682 | 425.7085 | 683 | 428.5886 | 684 | 431.4875 |
| 685 | 434.4051 | 686 | 437.3415 | 687 | 440.2970 | 688 | 443.2717 |
| 689 | 446.2655 | 690 | 449.2788 | 691 | 452.3116 | 692 | 455.3640 |
| 693 | 458.4361 | 694 | 461.5282 | 695 | 464.6402 | 696 | 467.7724 |
| 697 | 470.9249 | 698 | 474.0977 | 699 | 477.2911 | 700 | 480.5052 |
| 701 | 483.7400 | 702 | 486.9958 | 703 | 490.2726 | 704 | 493.5706 |
| 705 | 496.8900 | 706 | 500.2308 | 707 | 503.5932 | 708 | 506.9774 |
| 709 | 510.3835 | 710 | 513.8116 | 711 | 517.2619 | 712 | 520.7344 |
| 713 | 524.2294 | 714 | 527.7471 | 715 | 531.2874 | 716 | 534.8507 |
| 717 | 538.4370 | 718 | 542.0465 | 719 | 545.6793 | 720 | 549.3356 |
| 721 | 553.0155 | 722 | 556.7192 | 723 | 560.4469 | 724 | 564.1986 |
| 725 | 567.9746 | 726 | 571.7750 | 727 | 575.6000 | 728 | 579.4497 |
| 729 | 583.3242 | 730 | 587.2238 | 731 | 591.1486 | 732 | 595.0988 |
| 733 | 599.0744 | 734 | 603.0758 | 735 | 607.1030 | 736 | 611.1563 |
| 737 | 615.2357 | 738 | 619.3415 | 739 | 623.4738 | 740 | 627.6328 |
| 741 | 631.8187 | 742 | 636.0316 | 743 | 640.2717 | 744 | 644.5392 |
| 745 | 648.8343 | 746 | 653.1571 | 747 | 657.5079 | 748 | 661.8867 |
| 749 | 666.2939 | 750 | 670.7295 | 751 | 675.1937 | 752 | 679.6868 |
| 753 | 684.2089 | 754 | 688.7602 | 755 | 693.3409 | 756 | 697.9512 |
| 757 | 702.5913 | 758 | 707.2613 | 759 | 711.9615 | 760 | 716.6921 |
| 761 | 721.4531 | 762 | 726.2450 | 763 | 731.0678 | 764 | 735.9217 |
| 765 | 740.8070 | 766 | 745.7238 | 767 | 750.6723 | 768 | 755.6529 |
| 769 | 760.6655 | 770 | 765.7106 | 771 | 770.7882 | 772 | 775.8986 |
| 773 | 781.0420 | 774 | 786.2187 | 775 | 791.4287 | 776 | 796.6724 |
| 777 | 801.9500 | 778 | 807.2616 | 779 | 812.6075 | 780 | 817.9880 |
| 781 | 823.4031 | 782 | 828.8533 | 783 | 834.3386 | 784 | 839.8594 |
| 785 | 845.4158 | 786 | 851.0081 | 787 | 856.6365 | 788 | 862.3012 |
| 789 | 868.0025 | 790 | 873.7407 | 791 | 879.5158 | 792 | 885.3283 |
| 793 | 891.1783 | 794 | 897.0661 | 795 | 902.9919 | 796 | 908.9559 |
| 797 | 914.9585 | 798 | 920.9998 | 799 | 927.0801 | 800 | 933.1997 |
| 801 | 939.3588 | 802 | 945.5577 | 803 | 951.7966 | 804 | 958.0758 |

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|-----|-----------------------|-----|-----------------------|-----|-----------------------|-----|-----------------------|
| 805 | 964.3956 | 806 | 970.7561 | 807 | 977.1578 | 808 | 983.6008 |
| 809 | 990.0853 | 810 | 996.6118 | 811 | 1003.1800 | 812 | 1009.7910 |
| 813 | 1016.4450 | 814 | 1023.1420 | 815 | 1029.8820 | 816 | 1036.6650 |
| 817 | 1043.4930 | 818 | 1050.3640 | 819 | 1057.2800 | 820 | 1064.2400 |
| 821 | 1071.2460 | 822 | 1078.2960 | 823 | 1085.3920 | 824 | 1092.5340 |
| 825 | 1099.7220 | 826 | 1106.9570 | 827 | 1114.2380 | 828 | 1121.5670 |
| 829 | 1128.9420 | 830 | 1136.3660 | 831 | 1143.8370 | 832 | 1151.3570 |
| 833 | 1158.9250 | 834 | 1166.5420 | 835 | 1174.2080 | 836 | 1181.9240 |
| 837 | 1189.6890 | 838 | 1197.5050 | 839 | 1205.3710 | 840 | 1213.2890 |
| 841 | 1221.2570 | 842 | 1229.2770 | 843 | 1237.3480 | 844 | 1245.4720 |
| 845 | 1253.6480 | 846 | 1261.8770 | 847 | 1270.1600 | 848 | 1278.4950 |
| 849 | 1286.8850 | 850 | 1295.3290 | 851 | 1303.8270 | 852 | 1312.3810 |
| 853 | 1320.9900 | 854 | 1329.6540 | 855 | 1338.3740 | 856 | 1347.1510 |
| 857 | 1355.9840 | 858 | 1364.8750 | 859 | 1373.8230 | 860 | 1382.8290 |
| 861 | 1391.8930 | 862 | 1401.0160 | 863 | 1410.1970 | 864 | 1419.4380 |
| 865 | 1428.7390 | 866 | 1438.1000 | 867 | 1447.5220 | 868 | 1457.0040 |
| 869 | 1466.5480 | 870 | 1476.1530 | 871 | 1485.8210 | 872 | 1495.5510 |
| 873 | 1505.3440 | 874 | 1515.2010 | 875 | 1525.1210 | 876 | 1535.1050 |
| 877 | 1545.1540 | 878 | 1555.2680 | 879 | 1565.4470 | 880 | 1575.6930 |
| 881 | 1586.0040 | 882 | 1596.3820 | 883 | 1606.8280 | 884 | 1617.3410 |
| 885 | 1627.9220 | 886 | 1638.5710 | 887 | 1649.2900 | 888 | 1660.0780 |
| 889 | 1670.9350 | 890 | 1681.8630 | 891 | 1692.8620 | 892 | 1703.9310 |
| 893 | 1715.0730 | 894 | 1726.2860 | 895 | 1737.5730 | 896 | 1748.9320 |
| 897 | 1760.3650 | 898 | 1771.8720 | 899 | 1783.4530 | 900 | 1795.1090 |
| 901 | 1806.8410 | 902 | 1818.6490 | 903 | 1830.5330 | 904 | 1842.4940 |
| 905 | 1854.5330 | 906 | 1866.6500 | 907 | 1878.8450 | 908 | 1891.1190 |
| 909 | 1903.4730 | 910 | 1915.9060 | 911 | 1928.4200 | 912 | 1941.0160 |
| 913 | 1953.6930 | 914 | 1966.4520 | 915 | 1979.2940 | 916 | 1992.2190 |
| 917 | 2005.2270 | 918 | 2018.3200 | 919 | 2031.4980 | 920 | 2044.7620 |
| 921 | 2058.1110 | 922 | 2071.5470 | 923 | 2085.0700 | 924 | 2098.6800 |
| 925 | 2112.3790 | 926 | 2126.1670 | 927 | 2140.0440 | 928 | 2154.0110 |
| 929 | 2168.0690 | 930 | 2182.2170 | 931 | 2196.4580 | 932 | 2210.7910 |
| 933 | 2225.2170 | 934 | 2239.7360 | 935 | 2254.3500 | 936 | 2269.0580 |
| 937 | 2283.8620 | 938 | 2298.7620 | 939 | 2313.7590 | 940 | 2328.8530 |
| 941 | 2344.0450 | 942 | 2359.3350 | 943 | 2374.7250 | 944 | 2390.2140 |
| 945 | 2405.8040 | 946 | 2421.4960 | 947 | 2437.2890 | 948 | 2453.1850 |
| 949 | 2469.1840 | 950 | 2485.2860 | 951 | 2501.4940 | 952 | 2517.8060 |
| 953 | 2534.2250 | 954 | 2550.7500 | 955 | 2567.3820 | 956 | 2584.1230 |
| 957 | 2600.9720 | 958 | 2617.9310 | 959 | 2634.9990 | 960 | 2652.1790 |
| 961 | 2669.4710 | 962 | 2686.8740 | 963 | 2704.3910 | 964 | 2722.0220 |
| 965 | 2739.7670 | 966 | 2757.6270 | 967 | 2775.6040 | 968 | 2793.6970 |
| 969 | 2811.9080 | 970 | 2830.2380 | 971 | 2848.6870 | 972 | 2867.2550 |

| JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] | JND | L[cd/m ²] |
|------|-----------------------|------|-----------------------|------|-----------------------|------|-----------------------|
| 973 | 2885.9440 | 974 | 2904.7550 | 975 | 2923.6880 | 976 | 2942.7450 |
| 977 | 2961.9250 | 978 | 2981.2300 | 979 | 3000.6600 | 980 | 3020.2170 |
| 981 | 3039.9020 | 982 | 3059.7140 | 983 | 3079.6550 | 984 | 3099.7260 |
| 985 | 3119.9270 | 986 | 3140.2600 | 987 | 3160.7260 | 988 | 3181.3240 |
| 989 | 3202.0570 | 990 | 3222.9240 | 991 | 3243.9280 | 992 | 3265.0680 |
| 993 | 3286.3460 | 994 | 3307.7620 | 995 | 3329.3180 | 996 | 3351.0140 |
| 997 | 3372.8520 | 998 | 3394.8310 | 999 | 3416.9540 | 1000 | 3439.2210 |
| 1001 | 3461.6330 | 1002 | 3484.1910 | 1003 | 3506.8970 | 1004 | 3529.7500 |
| 1005 | 3552.7520 | 1006 | 3575.9030 | 1007 | 3599.2060 | 1008 | 3622.6610 |
| 1009 | 3646.2680 | 1010 | 3670.0300 | 1011 | 3693.9460 | 1012 | 3718.0180 |
| 1013 | 3742.2480 | 1014 | 3766.6350 | 1015 | 3791.1810 | 1016 | 3815.8880 |
| 1017 | 3840.7550 | 1018 | 3865.7850 | 1019 | 3890.9780 | 1020 | 3916.3350 |
| 1021 | 3941.8580 | 1022 | 3967.5470 | 1023 | 3993.4040 | | |

C Measuring the Accuracy With Which a Display System Matches the Grayscale Standard Display Function (Informative)

C.1 General Considerations Regarding Conformance and Metrics

To demonstrate conformance with the Grayscale Standard Display Function is a much more complex task than, for example, validating the responses of a totally digital system to DICOM messages.

Display systems ultimately produce analog output, either directly as Luminances or indirectly as optical densities. For some Display Systems, this analog output can be affected by various imperfections in addition to whatever imperfections exist in the Display System's Display Function that is to be validated. For example, there may be spatial non-uniformities in the final presented image (e.g., arising from film, printing, or processing non-uniformities in the case of a hardcopy printer) that are measurable but are at low spatial frequencies that do not ordinarily pose an image quality problem in diagnostic radiology.

It is worth noting that CRTs and light-boxes also introduce their own spatial non-uniformities. These non-uniformities are outside the scope of the Grayscale Standard Display Function and the measurement procedures described here. But because of them, even a test image that is perfectly presented in terms of the Grayscale Standard Display Function will be less than perfectly perceived on a real CRT or a real light-box.

Furthermore, the question "How close (to the Grayscale Standard Display Function) is close enough?" is currently unanswered, since the answer depends on psychophysical studies not yet done to determine what difference in Display Function is "just noticeable" when two nearly identical image presentations (e.g., two nearly identical films placed on equivalent side-by-side light-boxes) are presented to an observer.

Furthermore, the evaluation of a given Display System could be based either on visual tests (e.g., assessing the perceived contrast of many low-contrast targets in one or more test images) or by quantitative analysis based on measured data obtained from instruments (e.g., photometers or densitometers).

Even the quantitative approach could be addressed in different ways. One could, for example, simply superimpose plots of measured and theoretical analog output (i.e., Luminance or optical density) vs. P-Value, perhaps along with "error bars" indicating the expected uncertainty (non-repeatable variations) in the measured output. As a mathematically more elegant alternative, all the measured data points could be used as input to a statistical mathematical analysis that could attempt to determine the underlying Display Function of the Display System, yielding one or more quantitative values (metrics) that define how well the Display System conforms with the Grayscale Standard Display Function.

In what follows in this and the following annexes, an example of the latter type of metric analysis is used, in which measured data is analyzed using a "FIT" test that is intended to validate the shape of the Characteristic Curve and a "LUM" test that is intended to show the degree of scatter from the ideal Grayscale Standard Display Function. This approach has been applied, for example, to quantitatively demonstrate how improvements were successfully made to the Display Function of certain Display Systems.

Before proceeding with the description of the methodology of this specific metric approach, it should be noted that it is offered as one possible approach, not necessarily as the most appropriate approach for evaluating all Display Systems. In particular, the following notes should be considered before selecting or interpreting results from any particular metric approach.

1. There may be practical issues that limit the number of P-Values that can be meaningfully used in the analysis. For example, it may be practical to measure all 256 possible Luminances from a fixed position on the screen of an 8-bit video monitor, but it may be impractical to meaningfully measure all 4096 densities theoretically printable by a 12-bit film printer. One reason for the impracticality is the limited accuracy of densitometers (or even film digitizers). A second reason is that the film density measurements, unlike the CRT photometer measurements, are obtained from different locations on the display area, so any spatial non-uniformity that is present in the film affects the hardcopy measurement. Current hardcopy printers and densitometers both have absolute optical density accuracy limitations that are significantly worse than the change that would be caused by a change in just the least significant bit of a 12-bit P-Value. In general, selecting a larger number of P-Values allows, in principle, more localized aberrations from the Grayscale Standard Display Function to be "caught", but the signal-to-noise ratio (or significance) of each of these will be decreased.

2. If the measurement data for a particular Display System has significant "noise" (as indicated by limited repeatability in the data when multiple sets of measurements are taken), it may be desirable to apply a statistical analysis technique that goes beyond the "FIT" and "LUM" metric by explicitly utilizing the known standard deviations in the input data set, along with the data itself, to prevent the fitting technique from over-reacting to noise. See, for example, the section "General Linear Least Squares" in Reference C1 and the chapter "Least-Squares Fit to a Polynomial" in Reference C2. If measurement noise is not explicitly taken into account in the analysis, the metric's returned root-mean-square error of the data points relative to the fit could be misleadingly high, since it would include the combined effect of errors due to incorrectness in the Display Function and errors due to measurement noise.
3. If possible, the sensitivity and specificity of the metric being considered should be checked against visual tests. For example, a digital test pattern with many low-contrast steps at many ambient Luminances could be printed on a "laboratory standard" Grayscale Standard Display Function printer and also printed on a printer being evaluated. The resultant films could then be placed side-by-side on light-boxes for comparison by a human observer. A good metric technique should detect as sensitively and repeatably as the human observer the existence of deviations (of any shape) from the Grayscale Standard Display Function. For example, if a Display System has a Characteristic Curve that, for even a very short interval of DDL values, is too contrasty, too flat, or (worse yet) non-monotonic, the metric should be able to detect and respond to that anomaly as strongly as the human observer does.
4. Finally, in addition to the experimentally encountered non-repeatabilities in the data from a Display System, there may be reason to consider additional possible causes of variations. For example, varying the ordering of P-Values in a test pattern (temporally for CRTs, spatially for printers) might affect the results. For printers, switching to different media might affect the results. A higher confidence can be placed in the results obtained from any metric if the results are stable in the presence of any or all such changes.

C.2 Methodology

Step (1)

The Characteristic Curve of the test Display System should be determined with as many measurements as practical (see Section D.1, Section D.2, and Section D.3). Using the Grayscale Standard Display Function, the fractional number of JNDs are calculated for each Luminance interval between equally spaced P-Value steps. The JNDs/Luminance interval may be calculated directly, or iteratively. For example, if only a few JNDs belong to every Luminance interval, a linear interpolation may be performed. After transformation of the grayscale response of the Display System, the Luminance Levels for every P-Value are L_i and the corresponding Standard Luminance Levels are L_j ; d_j specifies the JNDs /Luminance-Interval on the Grayscale Standard Display Function for the given number of P-Values. Then, the JNDs/Luminance interval for the transformed Display Function are

$$r = d_j(L_{i+1} - L_i)(L_{j+1} + L_j) / ((L_{i+1} + L_i)(L_{j+1} - L_j)) \quad (C-1)$$

Additionally, an iterative method can be used to calculate the number of JNDs per Luminance interval, requiring only the Grayscale Standard Display Function that defines a JND step in Luminance given a Luminance value. This is done by simply counting the number of complete JND steps in the Luminance interval, and then the remaining fractional step. Start at the Luminance low end of the interval, and calculate from the Grayscale Standard Display Function the Luminance step required for one JND step. Then continue stepping from the low Luminance value to the high Luminance value in single JND steps, until the Luminance value of the upper end of the Luminance Range is passed. Calculate the fraction portion of one JND that this last step represents. the total number of completed integer JND steps plus the fractional portion of the last uncompleted step is the fractional number of JND steps in the Luminance interval.

Plot the number of JNDs per Luminance interval (vertical axis) versus the index of the Luminance interval (horizontal axis). This curve is referred to as the *Luminance intervals vs JNDs* curve. An example of a plot of Luminance intervals vs JNDs is shown in figure C-1. The plot is matched very well by a horizontal line when a linear regression is applied.



Figure C-1. Illustration for the LUM and FIT conformance measures

The JNDs/Luminance interval data are evaluated by two statistical measures [C4]. The first assesses the global match of the test Display Function with the Grayscale Standard Display Function. The second measure locally analyses the approximation of the Grayscale Standard Display Function to the test Display Function.

Step (2)

Two related measures of a regression analysis are applied after normal multiple linear regression assumptions are verified for the data [C3]. The first measure, named the *FIT* test, attempts to match the Luminance-Intervals-vs-JNDs curve of the test Luminance distribution with different order polynomial fits. The Grayscale Standard Display Function is characterized by exactly one JND per Luminance interval over the entire Luminance Range. Therefore, ideally, the data of JNDs/Luminance intervals vs index of the Luminance interval are best fit by a horizontal line of a constant number of JNDs/Luminance interval, indicating that both the local and global means of JNDs/Luminance interval are constant over the given Luminance Range. If the curve is better matched by a higher-order curve, the distribution is not closely approximating the Grayscale Standard Display Function. The regression analysis should test comparisons through third-order curves.

The second measure, the Luminance uniformity metric (LUM), analyzes whether the size of Luminance steps are uniform in perceptual size (i.e., JNDs) across the Luminance Range. This is measured by the Root Mean Square Error (RMSE) of the curve fit by a horizontal line of the JNDs/Luminance interval. The smaller the RMSE of the JNDs/Luminance interval, the more closely the test Display Function approximates the Grayscale Standard Display Function on a microscopic scale.

Both the FIT and LUM measures can be conveniently calculated on standard statistical packages.

Assuming the test Luminance distribution passes the FIT test, then the measure of quality of the distribution is determined by the single quantitative measurement (LUM) of the standard deviation of the JNDs/Luminance interval from their mean. Clinical practice is expected to determine the tolerances for the FIT and LUM values.

An important factor in reaching a close approximation of a test Display Function to the Grayscale Standard Display Function is the number of discrete output levels of the Display System. For instance, the LUM measure can be improved by using only a subset of the available DDLs while maintaining the full available output digitization resolution at the cost of decreasing contrast resolution.

While the LUM is influenced by the choice of the number of discrete output gray levels in the Grayscale Standard Display Function, the appropriate number of output levels is determined by the clinical application, including possible gray scale image processing that may occur independently of the Grayscale Standard Display Function standardization. Thus, PS3.14 does not prescribe a certain number of gray levels of output. However, in general, the larger the number of distinguishable gray levels available, the higher the possible image quality because the contrast resolution is increased. It is recommended that the number of necessary output driving

levels for the transformed Display Function be determined prior to standardization of the Display System (based on clinical applications of the Display System), so that this information can be used when calculating the transformation in order to avoid using gray scale distributions with fewer output levels than needed.

C.3 References

[C1] Press, William H, et al., Numerical Recipes in C, Cambridge University Press, 1988, Section "General Linear Least Squares"

[C2] Bevington, Phillip R., Data Reduction and Error Analysis for the Physical Sciences, McGraw-Hill, 1969, the chapter "Least-Squares Fit to a Polynomial" .

[C3] Kleinbaum DG, Kupper LL, Muller KE, Applied Regression Analysis and Other Multivariable Methods, Duxbury Press, 2nd Edition, pp 45-49, 1987.

[C4] Hemminger, B., Muller, K., "Performance Metric for evaluating conformance of medical image displays with the ACR/NEMA display function standard", SPIE Medical Imaging 1997, editor Yongmin Kim, vol 3031-25, 1997.

D Illustrations for Achieving Conformance with the Grayscale Standard Display Function (Informative)

The following sections illustrate how conformance with the Grayscale Standard Display Function may be achieved for emissive (soft-copy) Display Systems as well as systems producing image presentations (hard-copies) on transmissive and reflective media. Each section contains four sub-sections on 1) a procedure for measuring the system Characteristic Curve, 2) the application of the Grayscale Standard Display Function to the Luminance Range of the Display System, 3) the implementation of the Grayscale Standard Display Function, and 4) the application of the conformance metrics as proposed in Annex C.

It is emphasized that there are different ways to configure a Display System or to change its performance so that it conforms to the Grayscale Standard Display Function. In fact, conceivably, a Display System may calibrate itself automatically to maintain conformance with the Standard. Hence, the following three illustrations are truly only examples.

Luminance of any Display System, hard-copy or softcopy, may be measured with a photometer. The photometer should have the following characteristics:

- be accurate to within 3% or less of the absolute Luminance level across its full range of operation;
- have a relative accuracy of at least two times the least significant digit at any Luminance level in its range of operation;
- maintain this accuracy at Luminance levels that are one-tenth of the minimum measured Luminance of the Display System;
- have an acceptance angle that is small enough to incorporate only the measurement field without overlapping the surrounding background.

Note

The photometer may be of the type that attaches directly to the display face (with a suction cup) or of the type that is held away from the display face. If of the latter type, the photometer should be well baffled to exclude extraneous light sources, including light from the background area of the test pattern.

For a film Display System the photometer may be appropriately used to measure the background Illuminance and the Luminance of the light-box on which the film will be displayed. The Luminance characteristics of the film Display System may be measured directly with the photometer or indirectly using measured optical density of the film and the values for the measured background Illuminance and the light-box Luminance.

D.1 Emissive Display Systems

D.1.1 Measuring the System Characteristic Curve

Before the characteristic Luminance response of the emissive Display System is measured, it is allowed to warm up as recommended by the manufacturer and is adjusted such that it conforms to the manufacturer's performance specifications. In particular, adjustment procedures for setting the black and white levels of the display should be obtained from the Display System manufacturer. The goal is to maximize the dynamic Luminance Range of the display without introducing artifacts, resulting in the highest possible number of Just-Noticeable Differences (JNDs).

Note

A simple test that the system is set up properly can be performed by viewing the 5% and 95% squares in the SMPTE pattern. The perceived contrast between the 5% square and its 0% surrounding should be equal to the perceived contrast between the 95% square and a white square.

Measurement of the Characteristic Curve of the Display System may be accomplished using a test pattern (Figure D.1-1) consisting of:

- a square measurement field comprising 10% of the total number of pixels displayed by the system positioned in the center of the display;
- a full-screen uniform background of 20% of maximum Luminance surrounding the target.

Note

With a measurement field of 10% of the total number of displayed pixels and a surrounding set to 20% of maximum Luminance, internal light scatter in the monitor causes the Luminance Range to be typically comparable to that found in radiographs, such as a thorax radiograph, when displayed on the CRT monitor.



Figure D.1-1. The test pattern will be a variable intensity square in the center of a low Luminance background area.

Note

1. For example, on a 5-megapixel Display System with a matrix of 2048 by 2560 pixels, the target would be a square with 724 pixels on each side.
2. Ideally, the test pattern should fill the entire screen. Under certain windowed operating environments, it may be difficult to eliminate certain user-interface objects from the display, in particular, menu bars at the top of the screen. In this case, the background should fill as much of the screen as possible.

The Characteristic Curve of the Display System may be determined by

- turning off all ambient lighting (necessary only when a suction cup photometer is used or when a handheld photometer casts a shadow on the display screen);
- displaying the above test pattern;
- setting the DDL for the measurement field to a sequence of different values, starting with 0 and increasing at each step until the maximum DDL is reached;
- using a photometer to measure and record the Luminance of the measurement field at each command value.

As discussed in Annex C, the number and distribution of DDLs at which measurements are taken must be sufficient to accurately model the Characteristic Curve of the Display System over the entire Luminance Range.

Note

1. If a handheld photometer is used, it should be placed at a distance from the display screen so that Luminance is measured in the center of the measurement field, without overlapping the surrounding background. This distance can be calculated using the acceptance angle specification provided by the photometer manufacturer.
2. The exact number and distribution of DDLs should be based both on the characteristics of the Display System and on the mathematical technique used to interpolate the Characteristic Curve of the system. It is recommended that at least 64 different command values be used in the procedure.

3. Successive Luminance measurements should be spaced in time such that the Display System always reaches a steady state. It may be particularly important to allow the system to settle before taking the initial measurement at DDL 0.

As stated in the normative section, the effect of ambient light on the apparent Characteristic Curve must always be included when configuring a Display System to conform with the Grayscale Standard Display Function.

If a handheld photometer that does not cast a shadow on the display screen is used to measure the Characteristic Curve, then the Luminance produced by the display plus the effect of ambient light may be measured simultaneously.

When a suction cup photometer is used to take the Luminance measurements or when a handheld photometer casts a shadow on the display screen, all ambient lighting should be turned off while measuring the Characteristic Curve. The effect of ambient light is determined separately: The Display System is turned off, the ambient light is turned on, and the Luminance produced by scattering of ambient light at the display screen is measured by placing the photometer at a distance from the display screen so that its acceptance angle includes a major portion of the screen and that the measurement is not affected by direct illumination from areas outside the display screen. The Luminance related to ambient light is added to the previously measured Luminance levels produced by the Display System to determine the effective Characteristic Curve of the system.

Note

Changes in ambient lighting conditions may require recalibration of the display subsystem in order to maintain conformance to this standard.

In the following, an example for measurements and transformation of a Display Function is presented. The Display System for this example is a CRT monitor with display controller. It is assumed that the display controller allows a transformation of the DDLs with 8-bit input precision and 10-bit output precision.

The Luminance is measured with a photometer with a narrow (1°) acceptance angle. The ambient light level was adjusted as low as possible. No localized highlights were visible.

1. The maximum Luminance was measured when setting the DDL for the measurement field to the value that yielded the highest Luminance and the DDL of the surrounding to the middle DDL range. From this measurement, the Luminance - 20% of the maximum Luminance - for the surrounding of the measurement field was calculated.
2. The ambient light was turned off. With the photometer centered on the measurement field of the test pattern of Figure D.1-1, the Luminance was measured when varying the input level D_m in increments of 1 from 0 to 255. The transformation operator of the hypothetical display controller linearly mapped 8 bits on the input to 10 bits on the output. The measured data represent the Characteristic Curve $L = F(D_m)$ for the given operating conditions and this test pattern.
3. Next, the CRT was turned off and the ambient light turned on. The photometer was placed on the center axis of the CRT sufficiently far away so that it did not cast a shadow on the CRT face and its aperture intercepted light scattered from a major portion of the CRT face. The measured Luminance of 0.3 cd/m^2 produced by the ambient light on the CRT face was added to the measured Luminance values of the Characteristic Curve without ambient light. The result is listed in Table D.1-1 and plotted in Figure D.1-2.



Figure D.1-2. Measured Characteristic Curve with Ambient Light of an emissive Display System

Table D.1-1. Measured Characteristic Curve plus Ambient Light

| DDL | Luminance | DDL | Luminance | DDL | Luminance | DDL | Luminance |
|-----|-----------|-----|-----------|-----|-----------|-----|-----------|
| 0 | 0.305 | 1 | 0.305 | 2 | 0.305 | 3 | 0.305 |
| 4 | 0.305 | 5 | 0.305 | 6 | 0.305 | 7 | 0.305 |
| 8 | 0.305 | 9 | 0.305 | 10 | 0.305 | 11 | 0.307 |
| 12 | 0.307 | 13 | 0.307 | 14 | 0.307 | 15 | 0.307 |
| 16 | 0.307 | 17 | 0.307 | 18 | 0.307 | 19 | 0.307 |
| 20 | 0.307 | 21 | 0.307 | 22 | 0.310 | 23 | 0.310 |
| 24 | 0.310 | 25 | 0.310 | 26 | 0.310 | 27 | 0.320 |
| 28 | 0.320 | 29 | 0.320 | 30 | 0.330 | 31 | 0.330 |
| 32 | 0.340 | 33 | 0.350 | 34 | 0.360 | 35 | 0.370 |
| 36 | 0.380 | 37 | 0.392 | 38 | 0.410 | 39 | 0.424 |
| 40 | 0.442 | 41 | 0.464 | 42 | 0.486 | 43 | 0.512 |
| 44 | 0.534 | 45 | 0.562 | 46 | 0.594 | 47 | 0.626 |
| 48 | 0.674 | 49 | 0.710 | 50 | 0.750 | 51 | 0.796 |
| 52 | 0.842 | 53 | 0.888 | 54 | 0.938 | 55 | 0.994 |
| 56 | 1.048 | 57 | 1.108 | 58 | 1.168 | 59 | 1.232 |
| 60 | 1.294 | 61 | 1.366 | 62 | 1.438 | 63 | 1.512 |
| 64 | 1.620 | 65 | 1.702 | 66 | 1.788 | 67 | 1.876 |
| 68 | 1.960 | 69 | 2.056 | 70 | 2.154 | 71 | 2.248 |
| 72 | 2.350 | 73 | 2.456 | 74 | 2.564 | 75 | 2.670 |
| 76 | 2.790 | 77 | 2.908 | 78 | 3.022 | 79 | 3.146 |
| 80 | 3.328 | 81 | 3.460 | 82 | 3.584 | 83 | 3.732 |
| 84 | 3.870 | 85 | 4.006 | 86 | 4.156 | 87 | 4.310 |

| DDL | Luminance | DDL | Luminance | DDL | Luminance | DDL | Luminance |
|-----|-----------|-----|-----------|-----|-----------|-----|-----------|
| 88 | 4.456 | 89 | 4.608 | 90 | 4.766 | 91 | 4.944 |
| 92 | 5.104 | 93 | 5.268 | 94 | 5.444 | 95 | 5.630 |
| 96 | 5.864 | 97 | 6.050 | 98 | 6.238 | 99 | 6.438 |
| 100 | 6.610 | 101 | 6.820 | 102 | 7.024 | 103 | 7.224 |
| 104 | 7.428 | 105 | 7.644 | 106 | 7.872 | 107 | 8.066 |
| 108 | 8.298 | 109 | 8.528 | 110 | 8.752 | 111 | 8.982 |
| 112 | 9.330 | 113 | 9.574 | 114 | 9.796 | 115 | 10.060 |
| 116 | 10.314 | 117 | 10.560 | 118 | 10.820 | 119 | 11.080 |
| 120 | 11.340 | 121 | 11.620 | 122 | 11.880 | 123 | 12.180 |
| 124 | 12.460 | 125 | 12.700 | 126 | 13.020 | 127 | 13.300 |
| 128 | 13.720 | 129 | 14.020 | 130 | 14.360 | 131 | 14.640 |
| 132 | 14.940 | 133 | 15.300 | 134 | 15.600 | 135 | 15.900 |
| 136 | 16.240 | 137 | 16.560 | 138 | 16.920 | 139 | 17.220 |
| 140 | 17.600 | 141 | 17.940 | 142 | 18.240 | 143 | 18.640 |
| 144 | 19.120 | 145 | 19.460 | 146 | 19.800 | 147 | 20.260 |
| 148 | 20.560 | 149 | 20.920 | 150 | 21.360 | 151 | 21.760 |
| 152 | 22.060 | 153 | 22.520 | 154 | 22.960 | 155 | 23.300 |
| 156 | 23.700 | 157 | 24.080 | 158 | 24.600 | 159 | 24.980 |
| 160 | 25.520 | 161 | 26.040 | 162 | 26.480 | 163 | 26.700 |
| 164 | 27.380 | 165 | 27.620 | 166 | 28.040 | 167 | 28.580 |
| 168 | 28.980 | 169 | 29.400 | 170 | 29.840 | 171 | 30.540 |
| 172 | 30.800 | 173 | 31.380 | 174 | 31.880 | 175 | 32.400 |
| 176 | 33.060 | 177 | 33.400 | 178 | 34.040 | 179 | 34.400 |
| 180 | 34.840 | 181 | 35.360 | 182 | 35.900 | 183 | 36.400 |
| 184 | 37.060 | 185 | 37.400 | 186 | 38.300 | 187 | 38.420 |
| 188 | 39.160 | 189 | 39.760 | 190 | 39.980 | 191 | 40.840 |
| 192 | 41.540 | 193 | 41.900 | 194 | 42.800 | 195 | 43.060 |
| 196 | 43.620 | 197 | 44.520 | 198 | 44.620 | 199 | 45.500 |
| 200 | 46.100 | 201 | 46.380 | 202 | 47.400 | 203 | 47.600 |
| 204 | 48.320 | 205 | 49.060 | 206 | 49.380 | 207 | 50.320 |
| 208 | 50.920 | 209 | 51.600 | 210 | 52.420 | 211 | 52.680 |
| 212 | 53.520 | 213 | 54.220 | 214 | 54.620 | 215 | 55.420 |
| 216 | 56.100 | 217 | 56.600 | 218 | 57.400 | 219 | 57.820 |
| 220 | 58.660 | 221 | 59.320 | 222 | 59.800 | 223 | 60.720 |
| 224 | 61.520 | 225 | 62.240 | 226 | 63.040 | 227 | 63.480 |
| 228 | 64.460 | 229 | 65.020 | 230 | 65.500 | 231 | 66.500 |
| 232 | 66.960 | 233 | 67.840 | 234 | 68.600 | 235 | 68.980 |
| 236 | 70.040 | 237 | 70.520 | 238 | 71.420 | 239 | 72.180 |
| 240 | 72.900 | 241 | 73.980 | 242 | 74.580 | 243 | 75.320 |
| 244 | 76.200 | 245 | 76.540 | 246 | 77.720 | 247 | 78.220 |
| 248 | 79.200 | 249 | 79.880 | 250 | 80.420 | 251 | 81.560 |
| 252 | 81.960 | 253 | 83.140 | 254 | 83.720 | 255 | 84.340 |

D.1.2 Application of the Standard Formula

The section of the Grayscale Standard Display Function for the Luminance Range of the CRT monitor Display System is shown in Figure D.1-3. Minimum and maximum Luminance levels correspond to JND indices of $JND_{min} = 32.54$ and $JND_{max} = 453.85$, respectively. Thus, there are theoretically about 420 just-noticeable Luminance differences for the Standard Target (see Normative Section 6). Obviously, with 8-bit input digitization resolution, at best 256 noticeable Luminance increments can be realized.

D.1.3 Implementation of the Standard

The measured Characteristic Curve is interpolated for the available output levels D_{output} , in this case, yielding 1024 Luminance levels $L_{i,m}$. The Grayscale Standard Display Function is also interpolated between JND_{min} and JND_{max} ($JND = [JND_{max} - JND_{min}]/1023 = [453.85 - 32.54]/1023$) yielding 1024 Standard Luminance levels $L_{i,STD}$. Interpolations can be performed by a variety of techniques. Here, a cubic spline technique was employed.

For every $L_{i,STD}$, the closest $L_{j,m}$ is determined. The data pair I,J defines the transformation between D_{input} and D_{output} (Table D.1-2) by which the Luminance response of the Display System is made to approximate the Grayscale Standard Display Function.

Table D.1-2. Look-Up Table for Calibrating Display System

| Input | Output | Input | Output | Input | Output | Input | Output |
|-------|--------|-------|--------|-------|--------|-------|--------|
| 0 | 0 | 1 | 118 | 2 | 131 | 3 | 140 |
| 4 | 148 | 5 | 153 | 6 | 160 | 7 | 164 |
| 8 | 169 | 9 | 173 | 10 | 178 | 11 | 182 |
| 12 | 185 | 13 | 189 | 14 | 191 | 15 | 194 |
| 16 | 198 | 17 | 201 | 18 | 204 | 19 | 207 |
| 20 | 210 | 21 | 214 | 22 | 217 | 23 | 219 |
| 24 | 222 | 25 | 225 | 26 | 228 | 27 | 231 |
| 28 | 234 | 29 | 237 | 30 | 240 | 31 | 243 |
| 32 | 245 | 33 | 248 | 34 | 251 | 35 | 253 |
| 36 | 255 | 37 | 257 | 38 | 260 | 39 | 263 |
| 40 | 265 | 41 | 268 | 42 | 271 | 43 | 274 |
| 44 | 276 | 45 | 279 | 46 | 282 | 47 | 284 |
| 48 | 287 | 49 | 290 | 50 | 292 | 51 | 295 |
| 52 | 298 | 53 | 301 | 54 | 303 | 55 | 306 |
| 56 | 308 | 57 | 311 | 58 | 314 | 59 | 317 |
| 60 | 319 | 61 | 320 | 62 | 323 | 63 | 326 |
| 64 | 329 | 65 | 331 | 66 | 334 | 67 | 336 |
| 68 | 339 | 69 | 342 | 70 | 345 | 71 | 347 |
| 72 | 350 | 73 | 353 | 74 | 356 | 75 | 359 |
| 76 | 361 | 77 | 364 | 78 | 367 | 79 | 370 |
| 80 | 372 | 81 | 375 | 82 | 378 | 83 | 381 |
| 84 | 383 | 85 | 385 | 86 | 388 | 87 | 391 |
| 88 | 393 | 89 | 396 | 90 | 399 | 91 | 402 |
| 92 | 405 | 93 | 407 | 94 | 410 | 95 | 413 |
| 96 | 416 | 97 | 419 | 98 | 422 | 99 | 425 |
| 100 | 428 | 101 | 431 | 102 | 434 | 103 | 437 |
| 104 | 440 | 105 | 443 | 106 | 445 | 107 | 448 |
| 108 | 450 | 109 | 452 | 110 | 456 | 111 | 459 |

| Input | Output | Input | Output | Input | Output | Input | Output |
|-------|--------|-------|--------|-------|--------|-------|--------|
| 112 | 462 | 113 | 465 | 114 | 468 | 115 | 471 |
| 116 | 474 | 117 | 477 | 118 | 480 | 119 | 483 |
| 120 | 486 | 121 | 490 | 122 | 492 | 123 | 495 |
| 124 | 499 | 125 | 502 | 126 | 505 | 127 | 509 |
| 128 | 511 | 129 | 513 | 130 | 516 | 131 | 519 |
| 132 | 522 | 133 | 526 | 134 | 529 | 135 | 532 |
| 136 | 535 | 137 | 539 | 138 | 542 | 139 | 545 |
| 140 | 549 | 141 | 552 | 142 | 555 | 143 | 559 |
| 144 | 562 | 145 | 565 | 146 | 569 | 147 | 572 |
| 148 | 575 | 149 | 578 | 150 | 581 | 151 | 585 |
| 152 | 588 | 153 | 591 | 154 | 595 | 155 | 599 |
| 156 | 602 | 157 | 605 | 158 | 609 | 159 | 613 |
| 160 | 616 | 161 | 619 | 162 | 623 | 163 | 627 |
| 164 | 631 | 165 | 633 | 166 | 637 | 167 | 640 |
| 168 | 643 | 169 | 646 | 170 | 650 | 171 | 655 |
| 172 | 657 | 173 | 663 | 174 | 666 | 175 | 669 |
| 176 | 674 | 177 | 678 | 178 | 682 | 179 | 684 |
| 180 | 688 | 181 | 693 | 182 | 696 | 183 | 700 |
| 184 | 703 | 185 | 706 | 186 | 711 | 187 | 714 |
| 188 | 719 | 189 | 723 | 190 | 727 | 191 | 731 |
| 192 | 735 | 193 | 738 | 194 | 743 | 195 | 745 |
| 196 | 752 | 197 | 754 | 198 | 758 | 199 | 764 |
| 200 | 766 | 201 | 769 | 202 | 775 | 203 | 777 |
| 204 | 783 | 205 | 787 | 206 | 789 | 207 | 796 |
| 208 | 799 | 209 | 805 | 210 | 808 | 211 | 811 |
| 212 | 818 | 213 | 821 | 214 | 827 | 215 | 830 |
| 216 | 834 | 217 | 838 | 218 | 841 | 219 | 848 |
| 220 | 851 | 221 | 856 | 222 | 861 | 223 | 864 |
| 224 | 870 | 225 | 874 | 226 | 880 | 227 | 883 |
| 228 | 889 | 229 | 893 | 230 | 897 | 231 | 901 |
| 232 | 905 | 233 | 911 | 234 | 915 | 235 | 922 |
| 236 | 925 | 237 | 931 | 238 | 935 | 239 | 941 |
| 240 | 945 | 241 | 951 | 242 | 955 | 243 | 960 |
| 244 | 964 | 245 | 969 | 246 | 975 | 247 | 979 |
| 248 | 985 | 249 | 991 | 250 | 995 | 251 | 1002 |
| 252 | 1006 | 253 | 1012 | 254 | 1016 | 255 | 1023 |

D.1.4 Measures of Conformance

The FIT and the LUM metrics proposed in Annex C are applied to determine the macroscopic and microscopic approximation of the $L_{J,m}$ to the $L_{J,STD}$. Figure D.1-3 shows the perceptually linearized Display Function superimposed on the Grayscale Standard Display Function and Figure D.1-4 summarizes the results of the two metrics. A good global fit was achieved as demonstrated by the nearly horizontal-line fit as best fit obtained with the FIT metric. The RMSE is acceptable. All 255 P-Value intervals lead to JNDs on the transformed Display Function for the Standard Target.

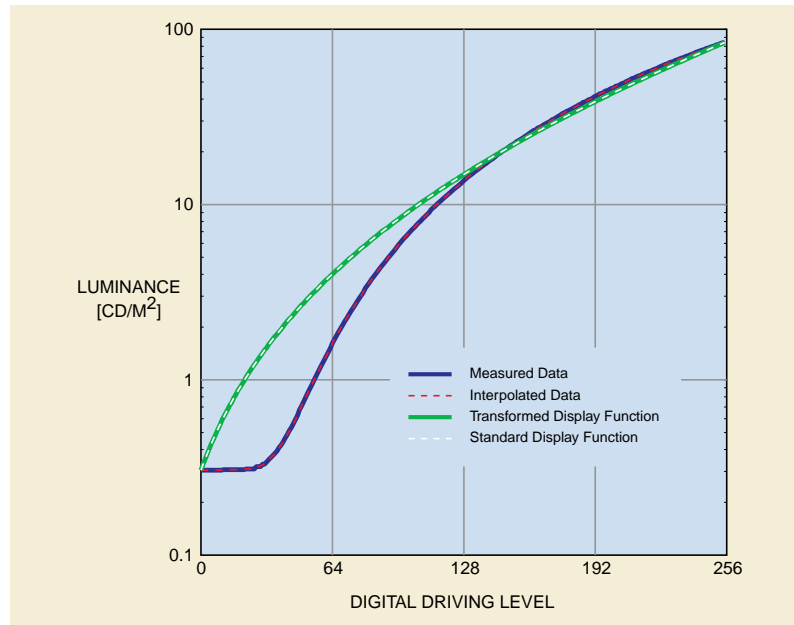


Figure D.1-3. Measured and interpolated Characteristic Curve, Grayscale Standard Display Function and transformed Display Function of an emissive Display System. The transformed Display Function for this Display System matches the Grayscale Standard Display Function and the two curves are superimposed and indistinguishable.

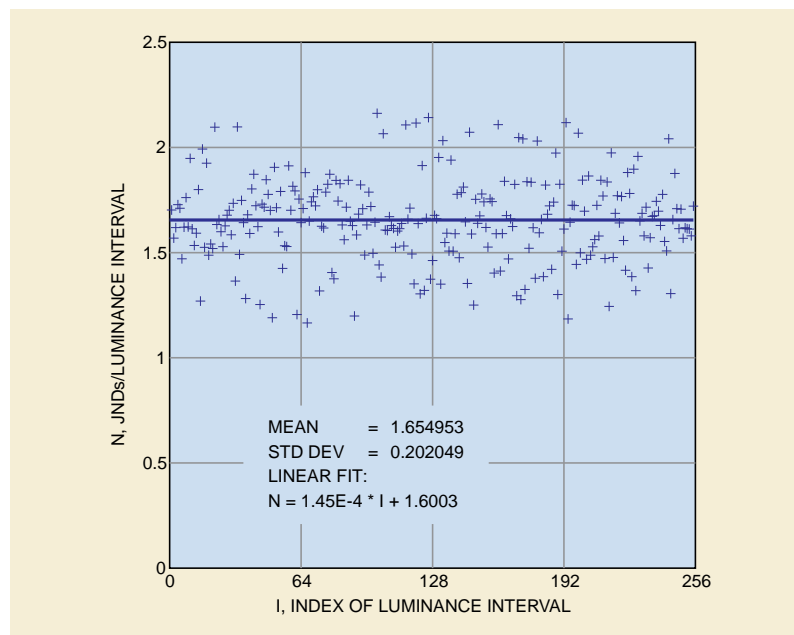


Figure D.1-4. LUM and FIT measures of conformance for a the transformed Display Function of an emissive Display System

D.2 Transparent Hardcopy Devices

D.2.1 Measuring the System Characteristic Curve

A transparent hardcopy device is exemplified by a laser printer (including processor) that prints (exposes and processes) one or more images on a sheet of transparent film (typically a 14" x 17" film). This film is eventually placed over a high Luminance light-box in a darkened room for viewing.

The Characteristic Curve for such a transparent hardcopy device is obtained by printing a test image consisting of a pattern of n bars, each bar having a specific numeric value (DDL). The optical density of each printed bar is then measured, using a transmission densitometer, for each of the printed bars.

To accurately define a printer's Characteristic Curve, it is desirable that n be as large as possible (to capture as many points as possible on the Characteristic Curve). However, the limitations on absolute quantitative repeatability imposed by the printer, processor, or media technologies may dictate that a much smaller value of n be used (to prevent a conformance metric that is sensitive to differences from becoming unstable and meaningless, as the density differences between adjacent bars become "in the noise" as the number of bars becomes large).

One example of a test image is a pattern of 32 approximately equal-height bars, spanning the usable printable region of the film, having 32 approximately equi-spaced DDLs as follows:

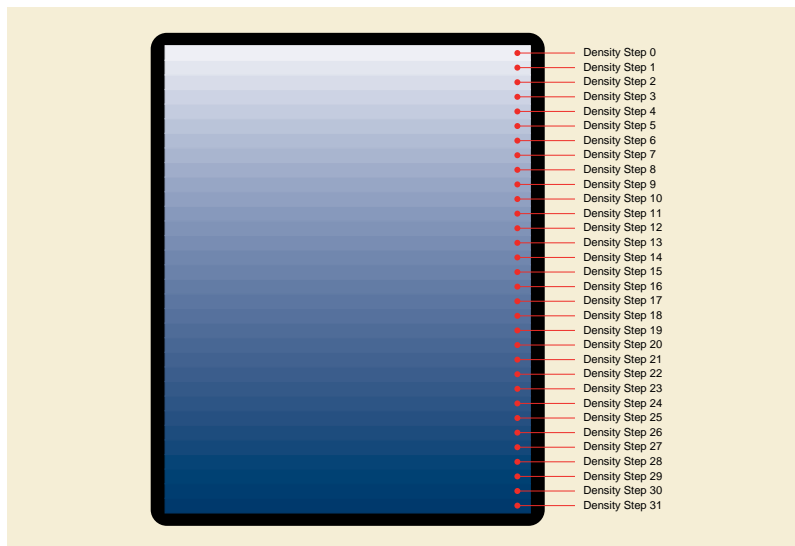


Figure D.2-1. Layout of a Test Pattern for Transparent Hardcopy Media

To define a test pattern with n DDLs for a printer with an N -bit input, the DDL of step # i can be set to

$$\text{DDL}_i = (2^{N-1})i/(n-1) \quad (\text{D.2-1})$$

rounded to the nearest integer.

The tabulated values of DDL_i and the corresponding measured optical densities OD_i constitute a Characteristic Curve of the printer.

D.2.2 Application of the Grayscale Standard Display Function

The films that are produced by transparent hardcopy printers are often brought to a variety of locations, where they may be viewed on different light-boxes and under a variety of viewing conditions. Accordingly, the approach of PS3.14 is to define, for hardcopy transparent printers, what densities (rather than Luminances) should be produced, and to provide here a method of applying the Grayscale Standard Display Function to the transparent hardcopy case, based on parameters that are typical of the expected range of light-box Luminances and other viewing parameters.

The specific parameters that are used in the following example are as follows:

L_0 (Luminance of light-box with no film present): 2000 cd/m²

L_a (ambient room light reflected by film): 10 cd/m²

D_{\min} (minimum optical density obtainable on film): 0.20

D_{\max} (maximum optical density desirable on film): 3.00.

The process of constructing a table of desired OD values from the Grayscale Standard Display Function begins with defining the Luminance Range and the corresponding range of the Just-Noticeable Difference Index, j . The minimum and maximum Luminance values are given respectively by

$$L_{\min} = L_a + L_0 10^{-D_{\max}} = 12.0 \text{ cd/m}^2 \quad (\text{D.2-2})$$

$$L_{\max} = L_a + L_0 10^{-D_{\min}} = 1271.9 \text{ cd/m}^2 \quad (\text{D.2-3})$$

Next, calculate the corresponding Just-Noticeable Difference Index values, j_{\min} and j_{\max} . For the current example, we obtain

$$j_{\min} = 233.32 \quad (\text{D.2-4})$$

$$j_{\max} = 848.75 \quad (\text{D.2-5})$$

This gives us the range of j -values that the printer should cover. The printer should map its minimum input (P-Value = 0) to j_{\min} and the corresponding L_{\min} . It should map its maximum input (P-Value = $2N-1$ where N is the number of input bits) to j_{\max} and the corresponding L_{\max} . At any intermediate input it should map its input proportionately:

$$j(PV) = j_{\min} + (j_{\max} - j_{\min}) \frac{PV}{2^N - 1} \quad (\text{D.2-6})$$

and target values for the Luminance given by the Standard's formula: $L(j(PV))$. This "targeting" consists of producing an optical density OD for this P-Value that will give the desired Luminance $L(j(PV))$ under the conditions of L_0 and L_a previously defined. The required density can thus be calculated as follows:

$$OD(PV) = -\log_{10} \frac{(L(j(PV)) - L_a)}{L_0} \quad (\text{D.2-7})$$

D.2.3 Implementation of the Grayscale Standard Display Function

Carrying this example into the even more specific case of a printer with an 8-bit input leads to the following table, which defines the OD's to be generated for each of the 256 possible P-Values.

Table D.2-1. Optical Densities for Each P-Value for an 8-Bit Printer

| P-Value | Optical Density (OD) | P-Value | Optical Density (OD) | P-Value | Optical Density (OD) | P-Value | Optical Density (OD) |
|---------|----------------------|---------|----------------------|---------|----------------------|---------|----------------------|
| 0 | 3.000 | 1 | 2.936 | 2 | 2.880 | 3 | 2.828 |
| 4 | 2.782 | 5 | 2.739 | 6 | 2.700 | 7 | 2.662 |
| 8 | 2.628 | 9 | 2.595 | 10 | 2.564 | 11 | 2.534 |
| 12 | 2.506 | 13 | 2.479 | 14 | 2.454 | 15 | 2.429 |
| 16 | 2.405 | 17 | 2.382 | 18 | 2.360 | 19 | 2.338 |
| 20 | 2.317 | 21 | 2.297 | 22 | 2.277 | 23 | 2.258 |
| 24 | 2.239 | 25 | 2.221 | 26 | 2.203 | 27 | 2.185 |
| 28 | 2.168 | 29 | 2.152 | 30 | 2.135 | 31 | 2.119 |
| 32 | 2.103 | 33 | 2.088 | 34 | 2.073 | 35 | 2.058 |
| 36 | 2.043 | 37 | 2.028 | 38 | 2.014 | 39 | 2.000 |
| 40 | 1.986 | 41 | 1.973 | 42 | 1.959 | 43 | 1.946 |

| P-Value | Optical Density (OD) | P-Value | Optical Density (OD) | P-Value | Optical Density (OD) | P-Value | Optical Density (OD) |
|---------|----------------------|---------|----------------------|---------|----------------------|---------|----------------------|
| 44 | 1.933 | 45 | 1.920 | 46 | 1.907 | 47 | 1.894 |
| 48 | 1.882 | 49 | 1.870 | 50 | 1.857 | 51 | 1.845 |
| 52 | 1.833 | 53 | 1.821 | 54 | 1.810 | 55 | 1.798 |
| 56 | 1.787 | 57 | 1.775 | 58 | 1.764 | 59 | 1.753 |
| 60 | 1.742 | 61 | 1.731 | 62 | 1.720 | 63 | 1.709 |
| 64 | 1.698 | 65 | 1.688 | 66 | 1.677 | 67 | 1.667 |
| 68 | 1.656 | 69 | 1.646 | 70 | 1.636 | 71 | 1.626 |
| 72 | 1.616 | 73 | 1.605 | 74 | 1.595 | 75 | 1.586 |
| 76 | 1.576 | 77 | 1.566 | 78 | 1.556 | 79 | 1.547 |
| 80 | 1.537 | 81 | 1.527 | 82 | 1.518 | 83 | 1.508 |
| 84 | 1.499 | 85 | 1.490 | 86 | 1.480 | 87 | 1.471 |
| 88 | 1.462 | 89 | 1.453 | 90 | 1.444 | 91 | 1.434 |
| 92 | 1.425 | 93 | 1.416 | 94 | 1.407 | 95 | 1.398 |
| 96 | 1.390 | 97 | 1.381 | 98 | 1.372 | 99 | 1.363 |
| 100 | 1.354 | 101 | 1.346 | 102 | 1.337 | 103 | 1.328 |
| 104 | 1.320 | 105 | 1.311 | 106 | 1.303 | 107 | 1.294 |
| 108 | 1.286 | 109 | 1.277 | 110 | 1.269 | 111 | 1.260 |
| 112 | 1.252 | 113 | 1.244 | 114 | 1.235 | 115 | 1.227 |
| 116 | 1.219 | 117 | 1.211 | 118 | 1.202 | 119 | 1.194 |
| 120 | 1.186 | 121 | 1.178 | 122 | 1.170 | 123 | 1.162 |
| 124 | 1.154 | 125 | 1.146 | 126 | 1.138 | 127 | 1.130 |
| 128 | 1.122 | 129 | 1.114 | 130 | 1.106 | 131 | 1.098 |
| 132 | 1.090 | 133 | 1.082 | 134 | 1.074 | 135 | 1.066 |
| 136 | 1.058 | 137 | 1.051 | 138 | 1.043 | 139 | 1.035 |
| 140 | 1.027 | 141 | 1.020 | 142 | 1.012 | 143 | 1.004 |
| 144 | 0.996 | 145 | 0.989 | 146 | 0.981 | 147 | 0.973 |
| 148 | 0.966 | 149 | 0.958 | 150 | 0.951 | 151 | 0.943 |
| 152 | 0.935 | 153 | 0.928 | 154 | 0.920 | 155 | 0.913 |
| 156 | 0.905 | 157 | 0.898 | 158 | 0.890 | 159 | 0.883 |
| 160 | 0.875 | 161 | 0.868 | 162 | 0.860 | 163 | 0.853 |
| 164 | 0.845 | 165 | 0.838 | 166 | 0.831 | 167 | 0.823 |
| 168 | 0.816 | 169 | 0.808 | 170 | 0.801 | 171 | 0.794 |
| 172 | 0.786 | 173 | 0.779 | 174 | 0.772 | 175 | 0.764 |
| 176 | 0.757 | 177 | 0.750 | 178 | 0.742 | 179 | 0.735 |
| 180 | 0.728 | 181 | 0.721 | 182 | 0.713 | 183 | 0.706 |
| 184 | 0.699 | 185 | 0.692 | 186 | 0.684 | 187 | 0.677 |
| 188 | 0.670 | 189 | 0.663 | 190 | 0.656 | 191 | 0.648 |
| 192 | 0.641 | 193 | 0.634 | 194 | 0.627 | 195 | 0.620 |
| 196 | 0.613 | 197 | 0.606 | 198 | 0.598 | 199 | 0.591 |
| 200 | 0.584 | 201 | 0.577 | 202 | 0.570 | 203 | 0.563 |
| 204 | 0.556 | 205 | 0.549 | 206 | 0.542 | 207 | 0.534 |

| P-Value | Optical Density (OD) | P-Value | Optical Density (OD) | P-Value | Optical Density (OD) | P-Value | Optical Density (OD) |
|---------|----------------------|---------|----------------------|---------|----------------------|---------|----------------------|
| 208 | 0.527 | 209 | 0.520 | 210 | 0.513 | 211 | 0.506 |
| 212 | 0.499 | 213 | 0.492 | 214 | 0.485 | 215 | 0.478 |
| 216 | 0.471 | 217 | 0.464 | 218 | 0.457 | 219 | 0.450 |
| 220 | 0.443 | 221 | 0.436 | 222 | 0.429 | 223 | 0.422 |
| 224 | 0.415 | 225 | 0.408 | 226 | 0.401 | 227 | 0.394 |
| 228 | 0.387 | 229 | 0.380 | 230 | 0.373 | 231 | 0.366 |
| 232 | 0.359 | 233 | 0.352 | 234 | 0.345 | 235 | 0.338 |
| 236 | 0.331 | 237 | 0.324 | 238 | 0.317 | 239 | 0.311 |
| 240 | 0.304 | 241 | 0.297 | 242 | 0.290 | 243 | 0.283 |
| 244 | 0.276 | 245 | 0.269 | 246 | 0.262 | 247 | 0.255 |
| 248 | 0.248 | 249 | 0.241 | 250 | 0.234 | 251 | 0.228 |
| 252 | 0.221 | 253 | 0.214 | 254 | 0.207 | 255 | 0.200 |

Plotting these values gives the curve of Figure D.2-3.



Figure D.2-3. Plot of OD vs P-Value for an 8-Bit Printer

D.2.4 Measures of Conformance

As an example, a bar pattern with 32 optical densities was printed on transmissive media (film). Beforehand, the printer had been set up to print over a density range from 0.2 (D_{\min}) to 3.0 (D_{\max}) and had been pre-configured by the manufacturer to use the Grayscale Standard Display Function, converted by the manufacturer into the table of target density values vs. P-Values described earlier.

The test pattern that was used for this was an 8-bit image consisting essentially of 32 horizontal bars. The 32 P-Values used for the bars were as follows: 0, 8, 16, 25, 33, 41, 49, 58, 66, 74, 82, 90, 99, 107, 115, 123, 132, 140, 148, 156, 165, 173, 181, 189, 197, 206, 214, 222, 230, 239, 247, 255.

For a given film, the 32 bars' optical densities were measured (near the middle of the film), converted to Luminances (using the standard parameters of light-box Luminance and reflected ambient light described earlier), and converted to Just-Noticeable Difference

Indices by mathematically computing $j(L)$ from $L(j)$, where $L(j)$ is the Grayscale Standard Display Function of Luminance L as a function of the Just-Noticeable Difference Index j . For each of the 31 intervals between consecutive measured values, a calculated value of "JNDs per increment in P-Values" was obtained by dividing the difference in Just-Noticeable Difference Index by the difference in P-Values for that interval. (In these calculations, density, L , and j are all floating-point variables. No rounding to integer values is done, so no truncation error is introduced.)

In this example, the film's data could be reasonably well fit by a horizontal straight line. That is, the calculated "JNDs per increment in P-Values" was essentially constant at 2.4. A mathematical fit yielded a slight non-zero slope (specifically, dropping from 2.5 to 2.3 as the P-Value went from 0 to 255), but the 0.2 total difference was considerably smaller than the noise that was present in the 31 individual values of "JNDs per increment in P-Value" so is of doubtful significance. (The "noise" referred to here consists of the random, non-repeatable variations that are seen if a new set of measured data (e.g., from a second print of the same test pattern) is compared with a previous set of measurements.)

No visual tests were done to see if a slope that small could be detected by a human observer in side-by-side film comparisons.

Incidentally, if one considers just the 32 original absolute measured densities (rather than differential values based on small differences), one finds, in this case, quite reasonable agreement between the target and measured optical densities (within the manufacturer's norms for density accuracy, at a given density). But if one uses any metric that is based on differential information over small intervals, the results must be considered more cautiously, since they can be strongly affected by (and may be dominated by) various imperfections that are independent of a device's "true" (or averaged over many cases) characteristic behavior.

D.3 Reflective Display Systems

This last example illustrates how conformance with the Grayscale Standard Display Function may be achieved for a thermal-dye-transfer paper printer/office-light system. The thermal-dye-transfer printer produces black-and-white grayscale prints on a semi-glossy 8-inch x 10-inch heavy-gauge paper. The print is illuminated uniformly by fluorescent lamps so that the minimum reflective density produces a Luminance of 150 cd/m^2 . The hypothetical transformation operator is assumed to have equal input and output digitization resolution of 8 bits.

D.3.1 Measuring the System Characteristic Curve

A print with a 64-step grayscale tablet was printed for DDLs 4, 8, 12, ..., 248, 252, 255. The reflection optical densities (from 0.08 to 2.80) were measured with a densitometer. The Luminance levels corresponding to the measured optical densities and illumination conditions are plotted in Figure D.3-1.



Figure D.3-1. Measured and interpolated Characteristic Curve and Grayscale Standard Display Function for a printer producing reflective hard-copies

D.3.2 Application of the Grayscale Standard Display Function

This last example illustrates how conformance with the Grayscale Standard Display Function may be achieved for a thermal-dye-transfer paper printer/office-light system. The thermal-dye-transfer printer produces black-and-white grayscale prints on a semi-glossy 8-inch x 10-inch heavy-gauge paper. The print is illuminated uniformly by fluorescent lamps so that the minimum reflective density produces a Luminance of 150 cd/m^2 . The hypothetical transformation operator is assumed to have equal input and output digitization resolution of 8 bits.

D.3.3 Implementation of the Grayscale Standard Display Function

The measured Characteristic Curve is interpolated for the available DDLs yielding 256 Luminance levels $L_{I,m}$. The Grayscale Standard Display Function is also interpolated between JND_{min} and JND_{max} ($DJND = [JND_{max} - JND_{min}]/255$) yielding 256 Standard Luminance levels $L_{I,STD}$.

For every $L_{I,STD}$, the closest $L_{I,m}$ is determined. The data pair I,J defines the transformation between D_{input} and D_{output} (Table D.3-1 and Figure D.3-2) by which the Luminance response of the Display System is made to approximate the Grayscale Standard Display Function.



Figure D.3-2. Transformation for modifying the Characteristic Curve of the printer to a Display Function that approximates the Grayscale Standard Display Function

Table D.3-1. Look-Up Table for Calibrating Reflection Hardcopy System

| P-Value | DDL | P-Value | DDL | P-Value | DDL | P-Value | DDL |
|---------|-----|---------|-----|---------|-----|---------|-----|
| 0 | 6 | 1 | 9 | 2 | 12 | 3 | 15 |
| 4 | 18 | 5 | 20 | 6 | 27 | 7 | 29 |
| 8 | 30 | 9 | 31 | 10 | 31 | 11 | 32 |
| 12 | 33 | 13 | 33 | 14 | 34 | 15 | 36 |
| 16 | 38 | 17 | 40 | 18 | 41 | 19 | 42 |
| 20 | 43 | 21 | 44 | 22 | 45 | 23 | 59 |
| 24 | 60 | 25 | 61 | 26 | 62 | 27 | 62 |
| 28 | 63 | 29 | 63 | 30 | 64 | 31 | 64 |
| 32 | 65 | 33 | 65 | 34 | 65 | 35 | 66 |
| 36 | 66 | 37 | 67 | 38 | 67 | 39 | 68 |
| 40 | 70 | 41 | 74 | 42 | 75 | 43 | 76 |
| 44 | 78 | 45 | 84 | 46 | 85 | 47 | 86 |
| 48 | 87 | 49 | 87 | 50 | 88 | 51 | 89 |
| 52 | 89 | 53 | 91 | 54 | 92 | 55 | 94 |
| 56 | 95 | 57 | 96 | 58 | 97 | 59 | 97 |
| 60 | 98 | 61 | 99 | 62 | 99 | 63 | 100 |
| 64 | 101 | 65 | 102 | 66 | 103 | 67 | 104 |
| 68 | 105 | 69 | 106 | 70 | 107 | 71 | 108 |
| 72 | 109 | 73 | 110 | 74 | 112 | 75 | 114 |
| 76 | 116 | 77 | 118 | 78 | 119 | 79 | 120 |
| 80 | 121 | 81 | 122 | 82 | 122 | 83 | 123 |

| P-Value | DDL | P-Value | DDL | P-Value | DDL | P-Value | DDL |
|---------|-----|---------|-----|---------|-----|---------|-----|
| 84 | 123 | 85 | 124 | 86 | 125 | 87 | 125 |
| 88 | 126 | 89 | 126 | 90 | 127 | 91 | 127 |
| 92 | 128 | 93 | 129 | 94 | 130 | 95 | 131 |
| 96 | 133 | 97 | 134 | 98 | 135 | 99 | 136 |
| 100 | 136 | 101 | 137 | 102 | 138 | 103 | 138 |
| 104 | 139 | 105 | 139 | 106 | 140 | 107 | 141 |
| 108 | 143 | 109 | 145 | 110 | 147 | 111 | 148 |
| 112 | 149 | 113 | 150 | 114 | 151 | 115 | 152 |
| 116 | 153 | 117 | 154 | 118 | 154 | 119 | 155 |
| 120 | 156 | 121 | 156 | 122 | 157 | 123 | 158 |
| 124 | 159 | 125 | 160 | 126 | 160 | 127 | 162 |
| 128 | 163 | 129 | 164 | 130 | 165 | 131 | 166 |
| 132 | 167 | 133 | 168 | 134 | 169 | 135 | 170 |
| 136 | 170 | 137 | 171 | 138 | 172 | 139 | 172 |
| 140 | 173 | 141 | 174 | 142 | 175 | 143 | 175 |
| 144 | 176 | 145 | 177 | 146 | 178 | 147 | 179 |
| 148 | 179 | 149 | 180 | 150 | 181 | 151 | 182 |
| 152 | 182 | 153 | 183 | 154 | 184 | 155 | 184 |
| 156 | 185 | 157 | 186 | 158 | 186 | 159 | 187 |
| 160 | 187 | 161 | 188 | 162 | 188 | 163 | 189 |
| 164 | 189 | 165 | 190 | 166 | 190 | 167 | 190 |
| 168 | 191 | 169 | 191 | 170 | 192 | 171 | 192 |
| 172 | 192 | 173 | 193 | 174 | 194 | 175 | 194 |
| 176 | 195 | 177 | 195 | 178 | 196 | 179 | 197 |
| 180 | 198 | 181 | 199 | 182 | 199 | 183 | 200 |
| 184 | 200 | 185 | 201 | 186 | 202 | 187 | 202 |
| 188 | 203 | 189 | 203 | 190 | 204 | 191 | 204 |
| 192 | 205 | 193 | 205 | 194 | 206 | 195 | 207 |
| 196 | 207 | 197 | 208 | 198 | 209 | 199 | 210 |
| 200 | 211 | 201 | 212 | 202 | 213 | 203 | 214 |
| 204 | 214 | 205 | 215 | 206 | 216 | 207 | 216 |
| 208 | 217 | 209 | 218 | 210 | 219 | 211 | 219 |
| 212 | 220 | 213 | 220 | 214 | 221 | 215 | 222 |
| 216 | 222 | 217 | 223 | 218 | 223 | 219 | 224 |
| 220 | 224 | 221 | 225 | 222 | 226 | 223 | 226 |
| 224 | 227 | 225 | 228 | 226 | 228 | 227 | 230 |
| 228 | 231 | 229 | 232 | 230 | 234 | 231 | 235 |
| 232 | 236 | 233 | 238 | 234 | 238 | 235 | 239 |
| 236 | 240 | 237 | 241 | 238 | 242 | 239 | 242 |
| 240 | 243 | 241 | 244 | 242 | 245 | 243 | 246 |
| 244 | 247 | 245 | 248 | 246 | 249 | 247 | 250 |
| 248 | 250 | 249 | 251 | 250 | 251 | 251 | 252 |

| P-Value | DDL | P-Value | DDL | P-Value | DDL | P-Value | DDL |
|---------|-----|---------|-----|---------|-----|---------|-----|
| 252 | 252 | 253 | 253 | 254 | 253 | 255 | 254 |

D.3.4 Measures of Conformance

The FIT and LUM metrics as proposed in Annex C are applied to determine the macroscopic and microscopic approximation of the $L_{J,m}$ to the $L_{i,STD}$. Figure D.3-3 shows the perceptually linearized Display Function superimposed on the Grayscale Standard Display Function and Figure D.3-4 summarizes the results of the two metrics. FIT provides as best fit of the JNDs/Luminance interval a straight line almost perfectly parallel to the horizontal axis indicating good global fit of the transformed Display Function with the Grayscale Standard Display Function. The RMSE computed by LUM is relatively large indicating more pronounced local deviations from the Grayscale Standard Display Function as, for example, with the soft-copy Display System illustrated in Section D.1. At least in part, the larger RMSE is due to the fact that the input and output digitization resolution for the transform are equal. The transformation table (Table D.3-1) and Figure D.3-2 show that several P-Values lead to the same Luminance levels on the transformed Display Function. In fact, only 205 of the 255 Luminance intervals lead to JNDs for the Standard Target.

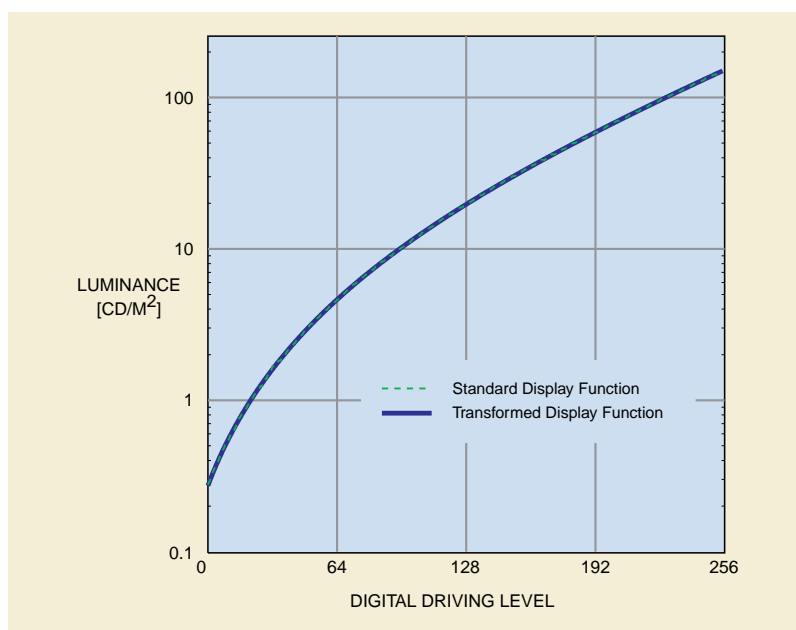


Figure D.3-3. Transformed Display Function and superimposed Grayscale Standard Display Function for a reflective hard-copy Display System. The transformed Display Function for this Display System matches the Grayscale Standard Display Function and the two curves are superimposed and indistinguishable.

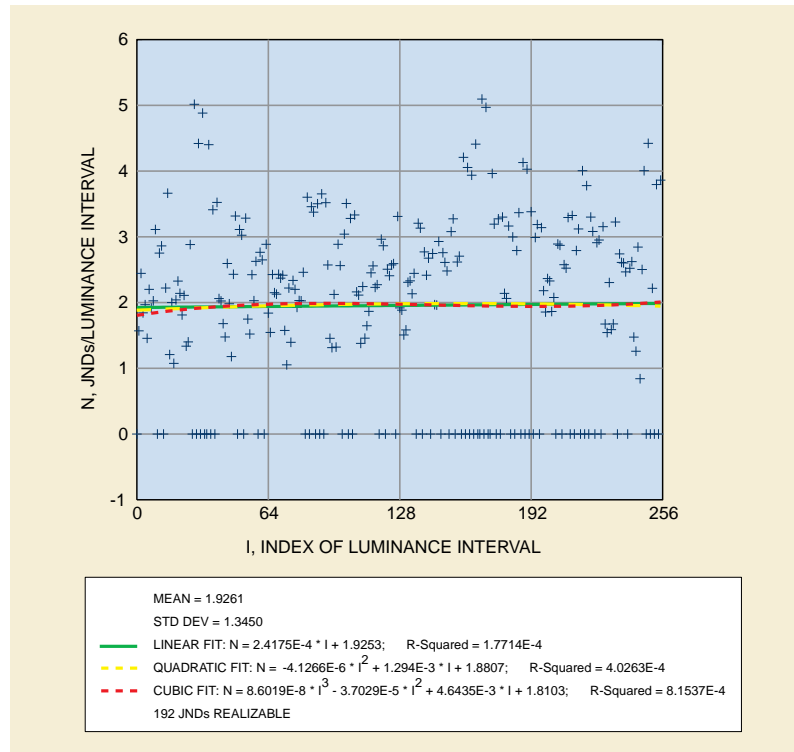


Figure D.3-4. Measures of conformance for a reflective hard-copy Display System with equal input and output digitization resolution of 8 bits

E Realizable JND Range of a Display Under Ambient Light (Informative)

Dynamic range is an often used measure of the information content that can be presented by a Display System. However, there are many definitions of dynamic range, and most such definitions do not take into account real world conditions that affect the actual amount of information that can be conveyed by a gray scale pixel. For example, Poynton [E1] refers to the *contrast ratio* of a gray scale display device as the ratio of display intensity between the brightest white and the darkest black of the particular display device in question. However, this definition of dynamic range applies to ideal viewing conditions. Real world conditions such as veiling glare, noise, spatial frequency content of the image, power supply saturation, and ambient lighting in a cathode ray tube (CRT) based viewing situation can degrade the measured dynamic range of the system significantly [E2, E3]. Because of all of these variables dynamic range is an ill-defined concept for a Display System.

Note

Veiling Glare is the phenomenon wherein internal light reflections inside the CRT creates a "background lighting" thus reducing the contrast range of the CRT device.

The methods used to determine the degree to which the Display Function of a Display System approximates the Grayscale Standard Display Function can also be used to define two measures that might better characterize the potential capabilities of a Display System to convey information content. Two measures, the theoretically achievable JNDs and the realized JNDs, are useful for comparing Display Systems [E4].

The number of theoretically achievable JNDs is simply the number of JNDs predicted by the visual model given the Luminance Range of the Display System used. The number of theoretically achievable JNDs of a Display System may be found from Table B-1 by counting the number of JNDs in the table that fall between the measured minimum and maximum Luminance of the Display System.

This number of JNDs may not actually be achievable due to resolution limitations of other portions of the Display System, in particular, the quantization resolution given by the finite number of bits per pixel driving the Display System. For example, Table B-1 may show that a particular Display System is capable of delivering 352 JNDs. However, if only 8 bits per pixel are presented to the Display System, the number of JNDs achievable cannot exceed $2^8 = 256$ JNDs because of the quantizing effect. In actual fact, the number of JNDs realized in a Display System will always be smaller than or equal to the lower of the theoretically achievable JNDs and the quantization limit. This is because some of the quantized values input to the display may not line up with the input value required to achieve the next JND.

The more useful number of realized JNDs, describes how many JNDs are actually achieved given the specifics of the Display System (i.e., the number of gray levels of contrast resolution and the distribution of Luminance values). This definition gives a measure of the information that can actually be conveyed by the system to a human observer, in essence, an informational dynamic range. This number is calculated beginning at the minimum Luminance of the Display System, and then stepping one JND in Luminance from the current Luminance value, and choosing the smallest increment in DDL value that achieves a step at least that large. Repeating this through all the available DDLs will produce a sequence of steps, all at least 1 JND apart, and the length of this sequence of steps is then the number of realizable JNDs of the Display System.

The methods of PS3.14 cannot precisely duplicate all of the real world sources of degradation in a Display System. However, this uniform method of determining the realizable number of JNDs should give a measure of the actual performance of a particular Display System that would be experienced by a human observer when using the Display System in a real world situation such as the viewing of radiological images in medicine.

References

- [E1] Poynton, C. "Frequently Asked Questions about Gamma", Internet <ftp://ftp.inforamp.net/pub/users/poynton/doc/colour/gamma-FAQ.pdf>
- [E2] Roehrig, H., Blume, H., Ji, T. and Browne, M.; "Performance Tests and Quality Control of Cathode Ray Tube Displays"; J. Digital Imaging, Vol. 3, No. 3, August 1990; pp. 134-145.
- [E3] Gray, J.; "Use of the SMPTE Test Pattern in Picture Archiving and Communication Systems"; J. Digital Imaging, Vol. 5, No. 1, February 1992; pp. 54-58.

[E4] Hemminger, B., Muller, K., "Performance Metric for evaluating conformance of medical image displays with the ACR/NEMA display function standard", SPIE Medical Imaging 1997, editor Yongmin Kim, vol 3031-25, 1997.