Color Processing for Digital Cinema 4: Measurements and Tolerances

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This series of articles on the color processing for digital cinema is based on the Engineering Guideline, SMPTE 432-1. The DC28 committee believed the information in that guideline would be more widely available if it were published as a series of articles in the *Journal*. This fourth article in the series describes the measurement techniques to be used in measuring light reflected from the theater screen. It also gives the aim values for each measurement and the allowable tolerances around those aims.

All the standards that will be needed for encoding and decoding of the color information for digital cinema have been published or will be published in the very near future. A standard only describes the final consensus of the people involved in writing that standard; it does not include the reasons for choosing what is in the standard. In addition, because each standard is self-contained, it is not always clear how all the standards dealing with one aspect of an area work together. For these reasons, an Engineering Guideline[1] was written. To make the information in that guideline more widely available, this series of articles has been written.

Many standards relating to the display of images using digital projectors in a theater, have been adopted, or are in the adoption process. However, only five standards[1-5] deal with the color encoding and color display in a theater. The current series of articles discusses those five color-related standards. This fourth article in the series explains the measurement techniques to be followed in the measurement of the light reflected from the screen. Then the aim values are listed for those measurements and the tolerances around those aims.

This series of articles will focus on the color encoding and decoding of the images for digital cinema as standardized by the SMPTE standards, recommended practices, and engineering guidelines. An article by Silva[6] and a book by Kennel[7] give considerably more information about the entire workflow for digital cinema.

Measurements of Projected Images

There are three SMPTE documents, SMPTE 431-1,[3] 431-2,[4] and 431-3,[5] which describe the measurements and the expected values for projector performance. These measurements are used to determine if a projector and the theater in which it is located are performing at the level of consistency expected and needed to ensure that all content shown on this projector in its theater will closely match the content shown on any projector in its theater. In this article, these three documents will be referred to as the SMPTE 431 documents.

SMPTE 431-1, "D-Cinema Exhibition Screen Luminance Level, Chromaticity, and Uniformity," is a standard that specifies the reference values and tolerances for the screen luminance level, white point chromaticity, and luminance and chromaticity uniformity of the projected light for the presentation of digital motion pictures in review rooms and commercial cinemas. Because the perception of color and contrast is dependent on the absolute luminance of an image, the goal of 431-1 is to achieve the look in the projected image that will correspond to the look produced during the mastering process.

SMPTE 431-2, "Reference Projector and Environment for Display of DCDM in Review Rooms and Theaters," is a recommended practice that defines the characteristics of the reference projector and its controlled environment. It also defines the acceptable tolerances around critical image parameters for both review room and theater applications. The goal of 431-2 is to provide a means for achieving consistent and repeatable color image quality for all digitally projected images.

SMPTE 431-2 states: "The Reference Projector is a practical device." There is no physical reference projector in an institution in the sense that there is a primary standard against which all other devices or materials are compared. It is instead a device defined by its characteristics and capabilities, not by its technology. It is doubtful that there is any physical device that exactly matches the defined characteristics of the reference projector. However, there are many physical digital projectors that match the defined characteristics of the reference projector within acceptable tolerances of the reference characteristics. Therefore, the term "reference projector" refers to two different devices: (1) the theoretical device defined exactly by the characteristics given in the various standards, and (2) any physical device that meets the characteristics, within the specified tolerances, defined for the theoretical reference projector.

SMPTE 431-3, "Projection Image Measurements," is a recommended practice that defines color patches and images and describes how to measure the light reflected from the screen in a theater. However, it does not specify the expected measurement results. The goal of 431-3 is to provide practices for theater on-screen measurements so that proper operating conditions can be maintained. These practices are independent of the projector technology and are not intended to be used for evaluating a projector against its published specifications. At the time SMPTE EG 432-1 and this article were written, SMPTE RP 431-3 was a draft document. In September 2007, the DC28 committee decided to abandon RP 431-3 and it will not issue as a Recommended Practice. However, the charts and measurement techniques described in that draft document are still applicable to the digital projection of motion images. Therefore, even though RP 431-3 is now abandoned, the measurements described here are valid and useful.

The following sections will describe the methods by which the measurements are to be made and the expected results from those measurements, based on the specifications in these three SMPTE 431 documents. The documents may change over time; therefore, before a measurement is made or a measurement result is compared to the value listed in this article, the appropriate document should be consulted to see if the standard value has changed. This article shows how the information in those documents can be used and includes the methods and expected results; however, these may change over time. The approach here is to take each measurement of a test pattern and explain it using the information from all three SMPTE documents. The measuring equipment, the locations in the theater from which the measurements are to be made, and the projector and theater environment, are the same for all measurements and test patterns. They will be explained first, then each measurement and test pattern will be explained.

Digital Cinema Distribution Master (DCDM) color encoding is designed to eliminate color artifacts. The recommended measurements, and tolerances around those measurements, indicate whether the system is performing as defined. However, there is still the possibility of having a system that works perfectly at those measured points, yet still has visible color artifacts. Therefore, several of the recommended measurements and tests are visual.

A number of the tables in this section have been copied directly from the SMPTE 431 documents. Those tables define tolerances and have columns labeled "Reference," "Review Room," and "Theater," or very similar words. It is recognized that different applications within the industry have different requirements for tolerances around the specifications. One must choose the appropriate tolerance based on the application and the need for different projectors to match different levels of precision. Tighter tolerances produce closer matches in the projected images. However, the cost of achieving and maintaining these tighter tolerances must be balanced against the need for those closer matches. In order to simplify communication, these column labels were chosen to define the varying levels of tolerance. These words mean:

Reference: The desired parameter level or value. This is the value relative to which the tolerances are defined.

Review Room: A theater in which critical image decisions are made.

Theater: A facility in which a paying customer views the images.

Measuring Equipment

SMPTE 431-3 recommends that only two measurements be made: the measurement of luminance and the measurement of chromaticity. It is recommended that the luminance be measured with either a photometer or a spectroradiometer having the spectral luminance response of the standard observer (photopic vision), as defined in CIE S002.[8] CIE S002 has information on two colorimetric observers, the 1931 observer (the 2-degree observer) and the 1964 observer (the 10-degree observer).

The SMPTE 431-3 luminance measurement should be made using the 2-degree observer data. The meter must have a minimum accuracy of ±0.5 cd/m² (±0.2 fL) for white field measurements and ±0.007 cd/m² (±0.002 fL) for black field measurements. The chromaticity must be measured with a spectroradiometer with a minimum accuracy of ±0.002 for the measurement of the x and y chromaticity coordinates at luminances above 10 cd/m². Color temperature meters do not have sufficient accuracy to meet these requirements for the measurement of either luminance or chrominance. In all cases, the measurements are made of light reflected from the screen. Therefore, the measuring instrument must be pointed at the screen when the measurement is made.

Measuring Locations Within the Review Room or Exhibition Theater

It is recommended that the measurements in a review room be taken at a height of approximately 1.1 m (43 in.) above the floor, at a distance of 1.5 to 3.5 screen heights from the screen, and at the place the color-grading operator would normally sit.

It is recommended that there be six measurement locations in an exhibition theater: three in the center row of the theater and three in the rear row. The three locations within each row are: left-edge seat, right-edge seat, and center seat. At each measurement location, it is recommended that the measuring equipment be approximately 1.1 m above the floor.

Projector and Theater Environment

The projector should be set-up and run according to the manufacturer's specifications. For these measurements, the projector must be turned on and allowed to stabilize for at least 20 min before any measurements are taken. The room lights in the theater need to be turned off except for lighting provided for safety reasons, in order to equal the normal theater operating conditions. The projector needs to receive images defined by the X'Y'Z' code values so that the entire D-Cinema system is being tested, from the server through the projector. Some projectors may come with built-in test patterns. Although these patterns may be very useful for some tests, they will not test the entire D-Cinema system if the X'Y'Z' signals do not come from a server.

Measurement of Theater Ambient Luminance

This is a measure of the light reflected from the screen from sources such as exit signs and foot lights, but not due to the projection mechanism. The light is measured under normal presentation conditions, but with the projector lamp doused or turned off. It is measured from the locations defined above, and from the center of the screen. For review rooms, the ambient light reflected by the screen needs to be less than 0.01 cd/m² (.0029 fL). For theaters, the ambient light reflected from the screen needs to be less than 0.03 cd/m² (.01 fL). Safety regulations and the placement of exit lights or access lights may result in a higher ambient light level; note that this will reduce the contrast of the projected image.

Measurement of the Luminance of White

There are two measurements for the white luminance. The absolute luminance is measured at the center of the screen. The luminance uniformity compares the measurement at the center of the screen to the measurement at the sides (for theaters and review rooms) or the corners (for review rooms) of the screen. The corner locations are defined as those points inset 5% ±1% of the screen width from both of the adjacent screen edges. The side locations are the points equidistant from two adjacent corner locations. The X'Y'Z' code values of the white are [3794 3960 3890].

The reference luminance values and the tolerances for review rooms and theaters are given in Table 1.

The reference chromaticity values and the tolerances for review rooms and theaters for the center of the screen are given in Table 2.

The tolerances for review rooms and theaters for the corners of the screen are given in Table 3. The tolerances for the corners are stated as a deviation from the chromaticity of the center, because the center has a

Parameter	Reference	Review Room Tolerances	Theater Tolerances
Luminance, center 100% white	48.0 cd/m² (14.0 fL)	±3.5 cd/m² (± 1.00 fL)	±10.2 cd/m² (± 3.00 fL)
Luminance sides	85% of center	80% to 90% of center	75% to 90% of center
Luminance corners	85% of center	80% to 90% of center	not specified

Table 1. White luminance values.

Parameter	Reference	Review Room Tolerances	Theater Tolerances
White Chromaticity, center	x = 0.314…y = 0.351	±0.002 x ±0.002 y	±0.006 x ±0.006 y

Table 2. White chromaticity values for the center of the screen.

tolerance associated with it. In order to make the screen appear as uniform as possible, it is better to have the corners differ from the center within a defined limit, rather than from the reference within a defined limit.

Although the luminance uniformity and the chromaticity uniformity are defined in relation to the center and an additional four or eight points on the screen, it is also stated that they should be symmetrically distributed about the geometric center of the screen and exhibit no abrupt changes. The problem that has been observed with some digital projectors is that the light on the screen at the specified locations falls within the specified tolerances, yet between those points, there are variations in color (chromaticity) that may be objectionable. Therefore, in an effort to minimize the number of measurements and the complexity of defining a series of measurements that would identify the problem, it is easier to look at a white field on the screen and see if there are obvious color deviations across the screen.

Measurement of the Luminance of Theater Black

The theater black is defined as the light reflected from the screen when the theater is in normal operating mode (safety lights on) and the projector is on and is being sent a set of very low code values. SMPTE 431-3 specifies that the code values of the image sent to the projector when measuring the theater black be [16 16 16]. Using the DCDM decoding equation for luminance,[4] the code value 16 corresponds to a luminance of 0.00003 cd/m^2. The projector may (and most likely will) put some light on the screen even when sent the code values [16 16 16]. Therefore, the theater black luminance most likely will be higher than the theater ambient luminance. There is no direct specification of the theater black. However, based on the specification of the white luminance and the sequential contrast (see the next section), the maximum theater black can be calculated. These values are shown in Table 4.

Measurement of the Sequential Contrast

The sequential contrast is defined as the luminance of the white divided by the luminance of the theater black. The specification of the sequential contrast and its tolerances are given in Table 5.

Measurement of the Intra-frame (Checkerboard) Contrast

The intra-frame contrast is measured using a checkerboard pattern with a 4 x 4 grid of alternating white and black patches. The code values for the white patches are [3794 3960 3890] and the code values for the black patches are [16 16 16]. The intra-frame contrast is computed as the sum of the luminances of the white patches divided by the sum of the luminances of the black patches. The specification of the intra-frame contrast and its tolerances are given in Table 6.

Visual Verification of Grayscale Tracking

The appearance of a neutral scale through the entire luminance range of the projector is essential to the display of high-quality images. It has been found that a visual estimate of the neutrality of a scale from white to black is a better test of the neutrality than any other measurements. Therefore, the recommendation on the verification of the grayscale tracking is a visual test.

The appearance of gray is relative to the color and luminance of the area surrounding the gray being

Parameter	Reference	Review Room Tolerances	Theater Tolerances
White Chromaticity, corners	within ±0.000 x ±0.000 y of the center	within ±0.008 x ±0.008 y of the center	within ±0.015 x ±0.015 y of the center

Table 3. White chromaticity tolerances for the corners of the screen.

Parameter	Reference	Review Room Tolerances	Theater Tolerances
Theater Black	0.024 cd/m^2	0.032 cd/m^2	0.040 cd/m^2

Table 4. Maximum theater black luminance levels.

Parameter	Reference	Review Room Tolerances	Theater Tolerances
Sequential Contrast	2000:1 minimum	1500:1 minimum	1200:1 minimum

Table 5. Sequential contrast values and tolerances.

Parameter	Reference	Review Room Tolerances	Theater Tolerances
Intra-frame Contrast	150:1 minimum	100:1 minimum	100:1 minimum

Table 6. Intra-frame contrast values and tolerances.

assessed. Therefore, for the assessment of the grayscale tracking, the background is set to a gray of the same chromaticity coordinates as the projector white point. Two gray scales are recommended: a black-to-white scale and a black-to-dark grayscale. Two scales are necessary because it is difficult to judge dark grays in the presence of bright whites. The black-to-white scale has a background luminance of 4.8 cd/m^2 (code values [1565 1633 1604]) above theater black, and the black-to-dark grayscale has a background luminance of 0.0064 cd/m^2 (code values [122 128 125]).

It is recommended that each grayscale test pattern be centered on the screen and occupy a rectangle the size of 20% of the screen height by 80% of the screen width. Each step needs to be 8% of the screen width. The black-to-white grayscale patches can be defined by the code values in Table 7. The black-to-dark grayscale patches can be defined by the code values in Table 8. Although this is a visual verification of grayscale tracking, Tables 7 and 8 show the chromaticity coordinates and luminance values of each of the steps. Examples of these two test images are shown in Figs. 1 and 2.

Although these tables have been copied from SMPTE 431-2, they are slightly modified. The luminance values in Tables 7 and 8 are the luminance values one can calculate from the Y' values. Therefore, if measurements of the luminance values are to be made in an actual theater, the luminance of the theater black luminance value must be added to the luminance values in these two tables, in order to calculate the expected measured luminance values. If measurements are made, they need to be made in the center of each gray patch. The luminance values in the tables in SMPTE 431-2 have a theater black of 0.02 cd/m^2 added to the luminance values calculated from the Y' values, because it is assumed in 431-2 that the sequential contrast ratio is 2000:1.

Visual Assessment of Contouring

Contouring is the appearance of steps or bands where only a continuous or smooth gradient is expected. Contouring is a function of many variables, and it is important to look at a series of test patterns with shallow gradations to simulate naturally occurring gradations in images. Examples include horizons, particularly at sunset or sunrise, and the natural falloff around high-intensity spotlights, particularly if diffused by atmosphere or lens filtration. These test pattern ramps need to have a step width of not less than four pixels with an increment of one code value per step, and need to be placed on a background equal to the minimum value in the ramp, so that the eye is adapted for maximum sensitivity.

The assessment of this artifact is visual. Look at each image or sequence of images from a normal viewing distance and under normal operating conditions and determine if any contouring (step in luminance) or color deviation from gray can be seen.

Dynamic fades to black are widely used in real-world content. The SMPTE 431 documents do not offer any specific test patterns for a dynamic fade test; however, a ramp that starts at what is described above, then slowly decreases in code values, would suffice. In use, the observer would watch the dynamic fade and judge it for any non-neutral colors in the fade series of images.

Measurement of the Transfer Function Exponent

The transfer function exponent controls the projected image contrast, which is an important part of the overall quality of the image. The tolerance around the transfer function exponent is designed to allow some variation in

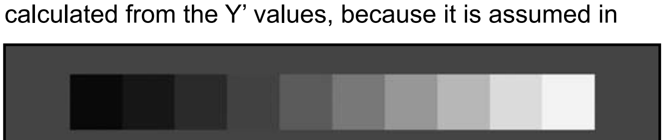

Figure 1. Black-to-white gray step-scale test pattern—example image.

Figure 2. Black-to-dark gray step-scale test pattern—example image.

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Step Number	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
1	379	396	389	0.314	0.351	0.12
2	759	792	778	0.314	0.351	0.73
3	1138	1188	1167	0.314	0.351	2.10
4	1518	1584	1556	0.314	0.351	4.43
5	1897	1980	1945	0.314	0.351	7.92
6	2276	2376	2334	0.314	0.351	12.72
7	2656	2772	2723	0.314	0.351	18.99
8	3035	3168	3112	0.314	0.351	26.87
9	3415	3564	3501	0.314	0.351	36.50
10	3794	3960	3890	0.314	0.351	48.00

Table 7. Black-to-white gray step-scale test pattern code values, luminance values, and chromaticity coordinates.

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Step Number	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
1	122	128	125	0.314	0.351	0.006
2	245	255	251	0.314	0.351	0.038
3	367	383	376	0.314	0.351	0.111
4	490	511	502	0.314	0.351	0.234
5	612	639	627	0.314	0.351	0.418
6	734	766	753	0.314	0.351	0.670
7	857	894	878	0.314	0.351	1.002
8	979	1022	1004	0.314	0.351	1.418
9	1101	1150	1129	0.314	0.351	1.928
10	1224	1277	1255	0.314	0.351	2.531

Table 8. Black-to-dark gray step-scale test pattern code values, luminance values, and chromaticity coordinates.

the system without seriously degrading image quality. This section describes how to measure that transfer function exponent. The decoding equation for luminance is:

(Equation 1)
$$Y = \left(\frac{52.37}{L}\right) * \left(\frac{Y'}{4095}\right)^{2.6}$$

where Y' is the DCDM code value for luminance, Y is luminance, and L is 48.00. This equation can be rewritten as:

(Equation 2)
$$\log(Y) = 2.6 * \log(Y') - 2.6\log(4095) + 2.6 * \log(52.37/L)$$

Image Parameters	Nominal Value (Reference Projector)	Tolerances (Review Rooms)	Tolerances (Theaters)
Exponent	2.6	±2%	±5%
Exponent	2.6	2.548 to 2.652	2.47 to 2.73

Table 9. Best fit slope of the transfer function exponent and tolerances for review rooms and theaters.

and simplifying gives:

(Equation 3) $$\log(Y) = 2.6 * \log(Y') - K$$

The value of K is unimportant in this test. If a series of white to gray frames, for example, the colors defined in Table 7, are projected and the luminance values are measured for each frame, a plot of log(Y) vs. log(Y') should give a straight line with a slope of 2.6. Because the X'Y'Z' values define tristimulus values above the theater black, the theater black luminance must be subtracted from each measured luminance before taking the log of the luminance. Table 9 shows the nominal value for this best fit slope and the tolerances, in both percentages, as specified in SMPTE 431-2, and in actual numbers, around the slope for review rooms and theaters.

Measurement of the Color Gamut (Color Primaries)

In an additive display, the color gamut is determined by the chromaticity coordinates and luminance values of the three primaries, the white, and the black. The white and the theater black were described earlier. The minimum set of color primaries is shown in Table 10. In practice, a projector may have a larger color gamut by using alternate primaries, as long as the projector can produce the chromaticity coordinates and luminance values from the code values in Table 10 within the color accuracy tolerances specified below. It is recommended that the measurement of the chromaticity coordinates and luminance values be made from the center of the screen when a full-field frame of the color primary code values is displayed by the projector. Table 10, like Tables 7 and 8, shows the luminance values calculated from the Y' values and do not include the theater black. Table 10 came from Table A.4 in RP 431-2 except that in Table 10, the Z' code value has been changed to 0 for the red primary. The 0 value is technically the correct red primary Z' value. The reason a Z' value of 100 was used in Table A.4 was that some devices will not pass a 0 code value, so the compromise 100 value was used. The X'Y'Z' code values [2901 2171 100] encode the chromaticity coordinates [0.6799 0.3200]. The difference of 0.0001 is well below what any instrument can measure and any person can see and is of no practical significance.

Specification of the Color Accuracy of Displayed Colors

Within the minimum color gamut specified for the reference projector, all colors need to be accurately reproduced within a tolerance of 4 delta E*ab. A discussion of delta E*ab was given in the previous article in this series.[9] In theory, this specification applies to all colors; however, in practice it would be impossible to display and measure all possible colors that can be encoded by the DCDM color encoding equations and displayed by a reference projector. Therefore, Table 11 gives a set of colors that can be used to verify the color accuracy of a system. It is considered that if these colors are within the tolerance limits, then all colors are most likely within the tolerances. The neutral colors 6 to 10 in Table 7 may also be used as tests of the color accuracy of any projector in its environment. As before, the luminance values in Table 11 are calculated from the Y' values and do not include the theater black. An example test image is shown in Fig. 3.

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	Code Values			Chromaticity Coordinates		Luminance
Primary	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
Red	2901	2171	0	0.6800	0.3200	10.06
Green	2417	3493	1222	0.2650	0.6900	34.64
Blue	2014	1416	3816	0.1500	0.0600	3.31

Table 10. RGB primary code values, luminance values, and chromaticity coordinates.

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Patch	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m^2
Red-1	2901	2171	100	0.6799	0.3200	10.06
Green-1	2417	3493	1222	0.2650	0.6900	34.64
Blue-1	2014	1416	3816	0.1500	0.0600	3.31
Cyan-1	2911	3618	3890	0.2048	0.3602	37.95
Magenta-1	3289	2421	3814	0.3424	0.1544	13.35
Yellow-1	3494	3853	1221	0.4248	0.5476	44.70
Red-2	2738	2171	1233	0.5980	0.3269	10.06
Green-2	2767	3493	2325	0.2884	0.5282	34.64
Blue-2	1800	1416	3203	0.1664	0.0891	3.31
Cyan-2	3085	3590	3756	0.2409	0.3572	37.19
Magenta-2	3062	2421	3497	0.3382	0.1838	13.35
Yellow-2	3461	3777	2065	0.3973	0.4989	42.44

Table 11. Color accuracy color patch code values, luminance values, and chromaticity coordinates.

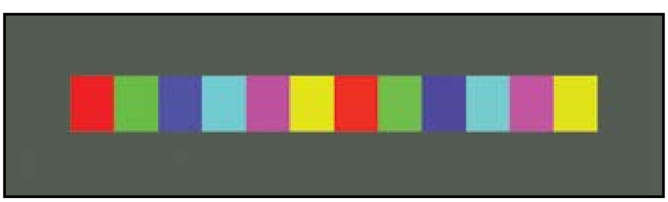

Figure 3. Color accuracy color patch—example image.

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