WHITE PAPER

Measuring and Correcting MicroLED Display Uniformity

Methods to Measure Subpixel Luminance and Chromaticity for Correction (Demura) and Quality Control

RADIANT VISION SYSTEMS

A Konica Minolta Company

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Introduction

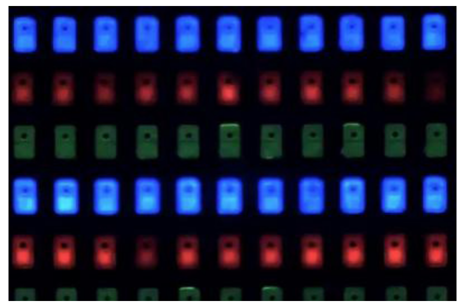
MicroLEDs (also called micro-LEDs, mLEDs, or µLEDs) continue to demonstrate performance advantages for displays, ushering in a new generation of backlit and direct-view illumination technology. MicroLED displays typically consist of an array of microscopic LEDs (light emitting diodes) that form the display's individual pixel and subpixel elements. This inorganic emissive technology offers many benefits over other display technologies including high brightness and contrast, wide color gamut, longevity, and high pixel density, improving visual performance in various ambient-light conditions from total darkness to full daylight and from multiple viewing angles.

These qualities make microLEDs especially attractive for applications such as smartphones and watches, augmented- and mixed-reality (AR/MR) devices, automotive display panels, and digital signage. Their benefits are driving significant investment in microLED technology and pushing market forecasts up to 330 million units by 2025.[1]

However, challenges associated with manufacturing high-quality microLED panels must be addressed before manufacturers achieve viable mass production and commercialization. Customers expect a high level of visual quality and performance, but at an affordable price. To keep component and production costs low, manufacturers need quality control solutions that reduce waste while increasing yield.

Unlike traditional LCD displays that rely on uniform backlights, microLEDs are individual emitters that commonly exhibit luminance and color variations at the pixel level. These variations require each microLED to be measured and adjusted individually to ensure visual uniformity across the display. A measurement and correction system for microLED manufacture must be capable of precise quantification of the output of each emissive element (the individual LED or subpixel). At the same time, the system must have very low takt times to correct the high quantity of emitters in a single display and support low-waste, high-volume production processes.

This white paper discusses how microLED measurement and correction requirements can be satisfied using imaging colorimeters, applying unique equipment specifications, calibrations, and software functions. The benefits of various measurement and correction methods will be demonstrated with test data and real-world application.



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A microLED subpixel array that uses very small (<100 µm) red, green, and blue LED chips in a matrix on a backplane.

The Challenge of MicroLED Display Uniformity

Achieving a consistent, uniform appearance has been a significant challenge of microLED display development, production, and commercialization. As individual emissive elements, microLEDs are driven independently and can exhibit a high degree of variability in luminance (Figure 1) and color (Figure 2). This variability can render microLED displays unusable unless corrections are applied to improve appearance.

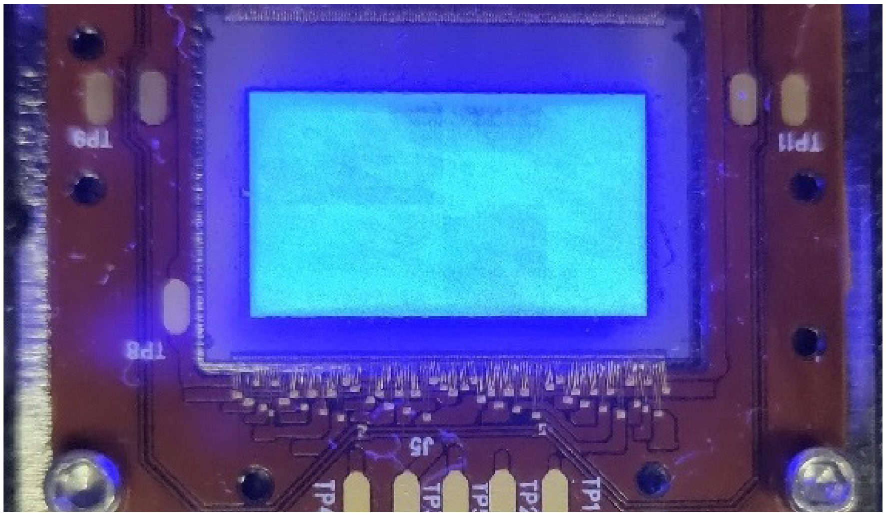

Figure 1 - *This close-up image of a microLED panel demonstrates the potential luminance and color uniformity issues due to varying pixel output across the display.*

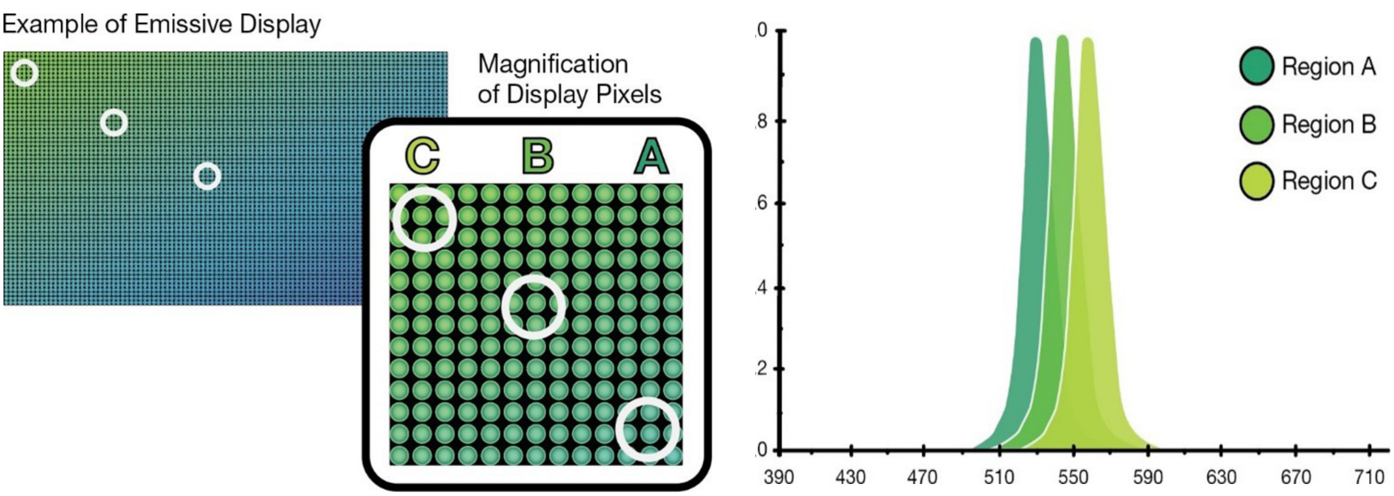

Figure 2 - *Illustration of an emissive display with color variability (far left), with magnification of areas across the display (display pixels) A, B, and C that vary in color (center left); example spectral data for A, B, and C (right).*

Variability is compounded because each microLED is typically a monochromatic subpixel (red, green, and blue) whose output is combined with other subpixels to produce the overall brightness and color of a single display pixel. This variability at the subpixel and pixel level manifests as a non-uniform appearance across the display, resulting in low yield of acceptable displays, rejection of expensive components, or costly rework (Figure 3).

Measurement of microLED subpixels (typically red, green, and blue) is necessary to quantify, evaluate, and potentially correct display output. However, microLEDs are challenging to measure accurately due to their variability in luminance and color, their size, proximity (small pixel pitch/density), and quantity per display. This makes them equally challenging to correct—especially at the speed needed to support commercial production throughput.

For emissive displays, new measurement methods that can detect and quantify the output of individual pixel and subpixel emissive elements are enabling display uniformity

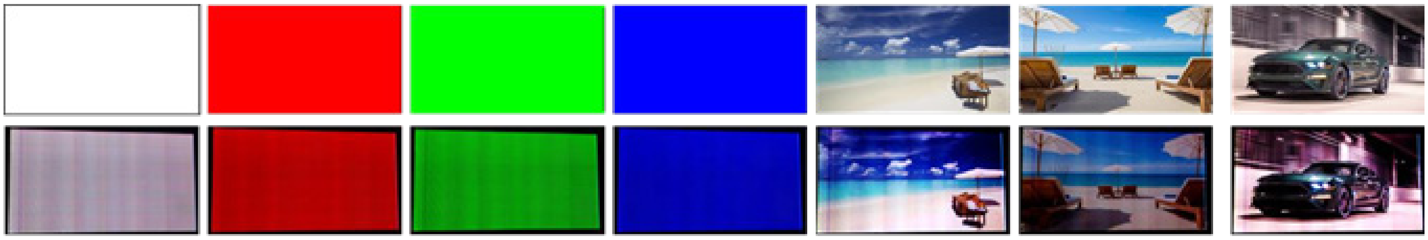

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Figure 3 - *Input signals for target color gamut of DCP-P3 (D65) (row 1), compared to microLED display output (row 2), where dominant vertical non-uniformity pattern and block-wise stamp marks are clearly seen.*[2]

correction. It is now possible to measure and correct the luminance and chromaticity output of each pixel, thereby producing displays with uniform appearance. This process—referred to as pixel uniformity correction, or "demura"—relies on the accuracy of subpixel-level luminance and color measurement to calculate accurate correction coefficients for each microLED.

Correcting Emissive Displays to Improve Yield

As display size scales, yields decline drastically, and the cost of each component is much higher. At a certain point, it becomes viable for manufacturers to perform correction (electronic compensation, or calibration) to improve display image quality. The concept is simple: by modifying the inputs to individual subpixels of an emissive display, dim pixels can be adjusted to a uniform brightness level, resulting in improved luminance uniformity and correct color across the display.

Display pixel uniformity correction requires, first, having in-display electronics that can control brightness of the individual subpixels and make adjustments based on a calculated correction factor for each subpixel. Second, a measurement system is required that can accurately quantify individual subpixel brightness and color, and compute specific correction factors for each of them. This method was originally developed to calibrate LED video screens (e.g., outdoor arena displays), and has been adapted for today's small, high-resolution emissive displays (OLED and microLED) using the demura pixel uniformity correction technique.

***Demura**: a method of improving the production yield of displays (e.g., OLED, microLED). First, measure the non-uniformity (mura) of the display as it would be perceived by human users of a device, registering each pixel/subpixel. A correction coefficient can then be calculated and applied to correct (literally, to "de-mura") the appearance of each pixel or subpixel. The corrected display can then be sold.*

Demura

The demura method employs three distinct steps:

1. Measure each subpixel in the display to calculate luminance values at each pixel coordinate location using a high-resolution imaging colorimeter. Accurate measurement values for each subpixel are essential. Test images are displayed on-screen to target subpixels of each color set, which enable measurements and correction factors to be computed for each set. For example, a green test image can be shown to illuminate all green subpixels. An imaging colorimeter measures and records the output of each individual green subpixel. This is repeated for all the primary colors and, usually, white.
2. Load the measurement data from each pixel's coordinate position into a coefficient calculator. Test analysis software is used to calculate correction factors that can be applied to normalize luminance and chromaticity discrepancies between pixels in the display.

3. Apply correction factors to the signals of each subpixel at each pixel location using an external control IC (integrated circuit) system.

Considerations for MicroLED Measurement

To individually measure and correct microLED emitters a solution must be capable of providing very low takt times to measure and correct the high quantity of emitters in a single display as efficiently as possible to support high-volume production processes.

Different display metrology systems offer benefits and drawbacks when applied to the various challenges of microLED color measurement. For example, a spectroradiometric system can achieve a high degree of color accuracy, but its slow takt times make it an inefficient solution to measure the millions of pixels that make up an entire microLED display.

Additionally, spectroradiometric systems typically have a spot size that is too large to provide the most accurate measurement of individual microLED emitters. A typical microLED is <100 micrometers (µm) square, with <50 µm quite common, and some as small as 3 µm.[3] Thus, a measurement system capable of measuring structures with a diameter no smaller than 0.075 mm would be insufficient to differentiate and measure the characteristics of individual microLED pixels smaller than 75 µm.

To meet production takt time requirements, some automated visual inspection systems are designed to provide high-speed measurement—for example, machine vision cameras. However, these systems do not have the photometric and colorimetric accuracy required to quantify subtle differences in luminance and chromaticity values, especially at the pixel level.

As will be shown, a calibrated, high-resolution imaging colorimeter provides both the accuracy and speed needed for production inspection, and thus offers an effective solution for pixel-level measurement of microLEDs. An optimal measurement solution to address commercial manufacturing demands would include:

- **Imaging colorimeter.** The advantages of imaging photometer and colorimeter systems include efficiency—the ability to detect all meaningful variations across displays in a single image, accomplishing multiple measurements at once: luminance, chromaticity, uniformity, contrast, pixel defects, etc. Another advantage is scope—the ability to capture the entire field of view (FOV) of a display in a single image, just as the device is viewed by a user. An imaging photometer measures luminance, while chromaticity measurements require an imaging colorimeter.
- **High resolution.** A microLED measurement system must have high-resolution imaging capabilities. High-resolution imaging provides the precision needed to distinguish and isolate each pixel and subpixel for measurement, and the efficiency to capture values for every pixel across increasingly high-resolution, pixel-dense displays in a single image.
- **Low noise.** Low-noise imaging capability is also needed. Image noise (which can include read noise, shot noise, or electronic noise), interferes with the clarity of an image. No matter how high the resolution of an imaging system (the number of

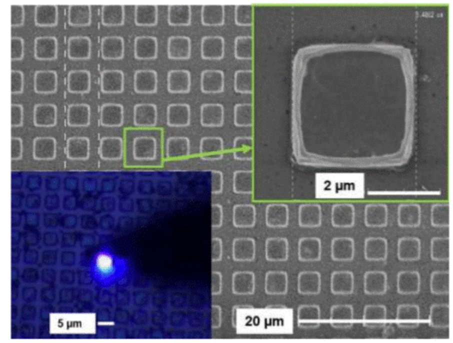


Image © Leti

SEM micrograph of 3-µm size / 5-µm pitch microLED array fabricated with direct bonding approach. Inset lower left is an optical photograph of microLED switched on.

megapixels (MP) of its sensor), if the system captures significant noise (yielding low signal-to-noise ratio, or SNR), then its effective resolution may be much lower.

- **Calibration.** To perform accurate measurement according to CIE standards, a metrology device must be carefully calibrated. A common method uses reference data captured by a spectroradiometer to calibrate the response of an imaging colorimeter. Enhanced Color Calibration™ (ECC) is an algorithm-based calibration method shown to have high accuracy (for details, see the section below titled Enhanced Color Calibration).

- **Test & Analysis Tools.** Image processing software enables manufacturers to optimize and run tests on a captured image. Ideally, an analysis package for display metrology would include tools to detect and quantify luminance, chromaticity, uniformity, contrast, pixel and line defects, display mura, and other qualities.

Importance of Measurement Accuracy: Luminance and Chromaticity

In 1931, the Commission Internationale de L'éclairage (CIE) defined a standard for scientifically quantifying the physical properties of color as perceived by a human observer, enabling accurate mathematical representation and reproduction of those colors (Figure 4).

To ensure quality, a metrology system that can mimic the human eye's response to light and color is vital for accurate measurement and correction of microLED display devices. Display pixels can be quantified based on mathematical formula of the CIE standard to provide chromaticity coordinates within the CIE color space.[4]

Tristimulus (XYZ) color filters on a rotating filter wheel enable color measurement according to standard CIE color-matching functions and chromaticity values. Light entering the metrology device is passed through the respective filters and then captured by a sensor (Figure 5). The filters adjust the incoming light, blocking certain wavelengths (such as UV that are invisible to the human eye) so that the sensors capture a measurement image with values that are as close as possible to what the human eye sees.

Tristimulus Systems

A recent study (Jensen, Piehl, and Renner 2020)[5] demonstrates the high degree of accuracy of a tristimulus system in matching human color perception (for details, refer to the section below titled Measurement Accuracy Study: Tristimulus System).

Enhanced Color Calibration™

Imaging systems require calibration data supplied via a spectrometer or other device to ensure measurement accuracy. Enhanced Color Calibration (ECC) from Radiant Vision Systems provides the highest level of color measurement accuracy via advanced calibration algorithms. The ECC method creates a 12-element correction calibration matrix in order to maximize the ability of the color measurement system to tolerate variability (provide accurate color measurement over a large area of the CIE color space) from a calibrated color value (a Calibration Point; see Figure 6).

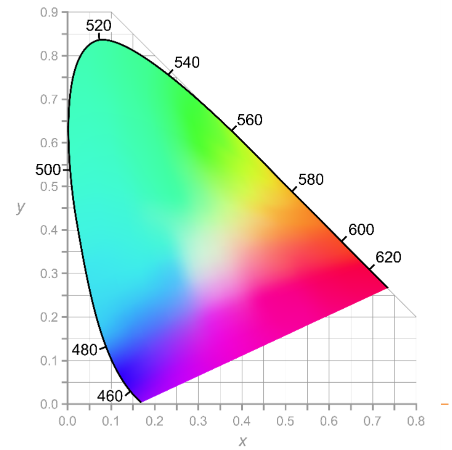


Figure 4 - *A graphical representation of the CIE 1931 color space, quantifying all colors visible to the human eye. The black numbers give the visible spectrum in wavelengths, while perceived colors are represented as coordinate points (x and y) within these limits.*

Figure 5 - *A CIE-matched tristimulus filter wheel system (shown here inside a ProMetric® I-Series Imaging Colorimeter) enables a measurement device to capture light and color as perceived by the human eye.*

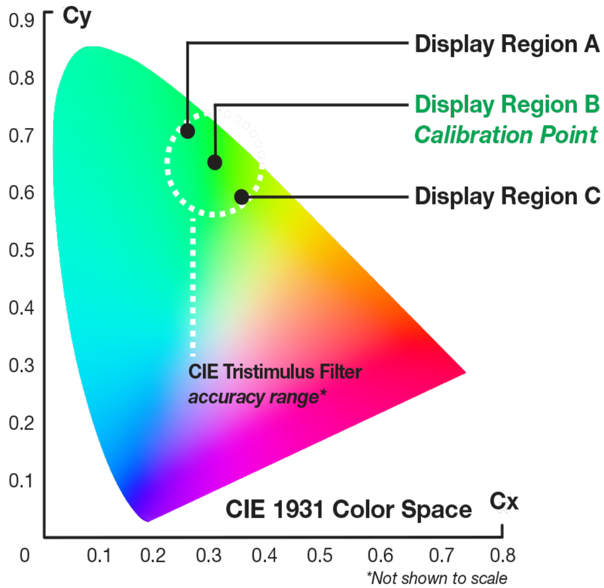


Figure 6 - *An innately close spectral response between tristimulus filter systems and CIE color-matching functions combined with ECC enables a tristimulus imaging colorimeter to continue to provide accuracy even as source spectral data deviates further from the calibration point. This chart illustrates an expected accuracy limit (area within the white dotted line circle) for a tristimulus imaging colorimeter with values A, B, and C plotted from Figure 2.*

Measurement Accuracy Study: Tristimulus System

This study looked at the color measurement accuracy of a CIE tristimulus filter imaging colorimeter system (a Radiant Vision Systems ProMetric® I29 (29 MP) Imaging Colorimeter) using ECC compared to a reference meter (a spectroradiometer). LEDs of different colors were measured by the reference meter and by the imaging colorimeter.

First, the imaging colorimeter was calibrated to a base output for each LED (using ECC). Then, the systems measured each LED at different output levels (LED variability was introduced by supplying different current levels). The accuracy of the imaging colorimeter was defined by its ability to match reference meter measurements as chromatic distance of the LED output increased from the system calibration point.

Full details and results of the study can be found in: Jensen, J., Piehl, A., and Renner, W., "Evaluating tristimulus and Bayer pattern matching system accuracy for color measurement based on CIE color-matching functions," presented at the 34th annual electronic displays conference (edC), January 2020.

Results

The tabular measurement data shown in Table 1 and plotted in Figure 7 and Figure 8 demonstrate that a tristimulus system provides accurate luminance and chromaticity values across introduced LED source variation. The tristimulus system accurately measures nearly the entire range of variation exhibited by each LED test source (at each supplied current) as indicated in Table 1, Parts A and B.

In all but a few measurements, the dominant wavelength of the tristimulus system measurements compared to the reference (∆Dom. Wv) showed a difference of less than 1 nm, indicating a high degree of accuracy for a tristimulus imaging colorimeter with ECC. These results demonstrate that a tristimulus system is suitable to accurately measure colored LEDs with a high degree of accuracy in both luminance and chromaticity—even as sources vary widely from the calibration point. In this study, the introduced variability of most of the LED test sources exceeded the expected variability of microLEDs. A tristimulus system is recommended for ensuring efficient and accurate display correction where source variation is high, or tolerance for variation is limited.

Results also demonstrate the robustness of a tristimulus system for accurately measuring across white LEDs (Table 1, Part C). These results indicate that a tristimulus imaging colorimeter can be used for wafer-level inspection, to address pick-and-place applications for microLED displays, and for general binning operations for both colored LEDs and white LEDs (Figures 7 and 8).

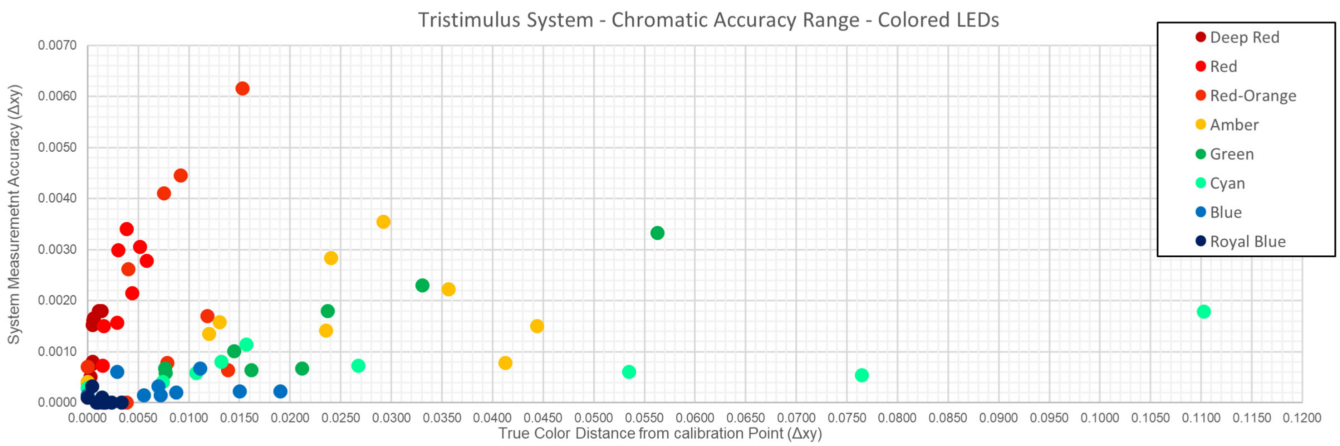


Figure 7 - *Tristimulus system (ProMetric® I29 (29 MP) Imaging Colorimeter) accuracy range for color variation across colored and white LED test sources.*

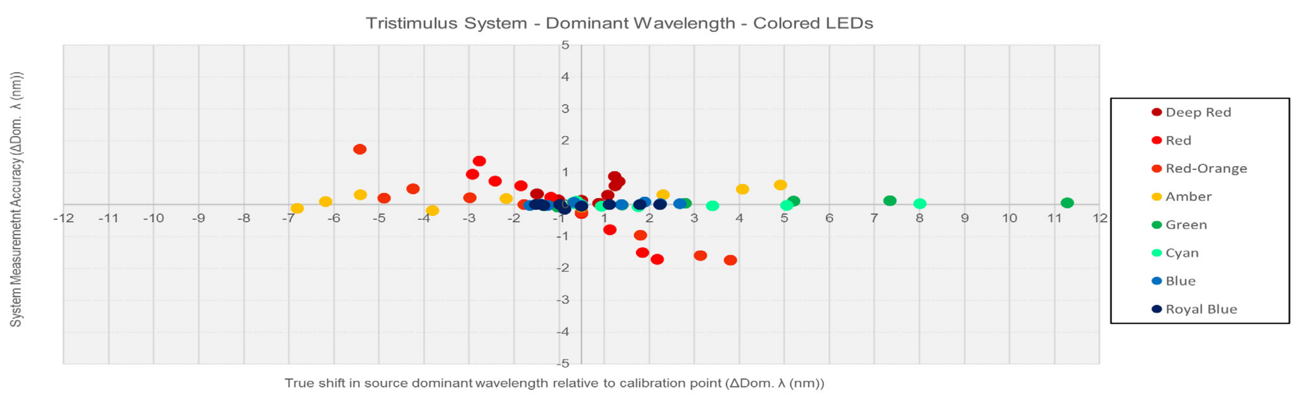


Figure 8 - *Plot showing true LED source variation at each current level (as measured by the reference spectroradiometer) based on ± nm change in dominant wavelength from the calibration point (x-axis). This axis gives the range of variation observed for each LED. The tristimulus system (ProMetric I29) measurement accuracy is shown as a ± nm difference from the reference measurement at each current level for each LED source (y-axis).*

Table 1, Part A - *Measurement data captured by a tristimulus imaging colorimeter system (ProMetric I29) versus a reference meter (spectroradiometer). Tan row of cells indicates the calibration condition for each source. Values measured by the test system are reported in the columns under Camera. Values measured by the reference meter (at the same time and within the same conditions) are reported under Reference. The error between dominant wavelength values measured by the test system and the reference meter is reported under Results in the columns ΔDom. Wv (nm), ΔLv (%), Δx, Δy, and Δxy.*

	Tristimulus System vs. Reference Measurement Agreement (xy)														
	LED	Camera				Reference					Result				
	Peak Wv (nm)	Dom. Wv (nm)	Lv	x	y	Dom. Wv (nm)	Lv	x	y	Δxy from Cal. Point	ΔDom. Wv (nm)	ΔLv (%)	Δx	Δy	Δxy
	658	643	3.7	0.721	0.279	642.3	3.7	0.719	0.279	**0.001**	0.7	-0.3	-0.002	0.001	0.002
	659	643.1	19	0.721	0.278	642.2	19.1	0.720	0.279	**0.001**	0.9	-0.5	-0.001	0.001	0.002
	660	642.8	36.9	0.721	0.279	642.2	37	0.720	0.279	**0.001**	0.6	-0.5	-0.001	0.001	0.002
	662	642.4	68.2	0.721	0.279	642.1	68.5	0.720	0.279	**0.001**	0.3	-0.4	-0.001	0.000	0.001
DEEP RED	664	641.9	93.8	0.720	0.279	641.9	94.2	0.719	0.280	**0.000**	0	-0.4	-0.001	0.000	0.001
	666	641.6	113.6	0.719	0.280	641.5	114.3	0.719	0.280	**0.001**	0.1	-0.6	0	0.000	0.000
	668	641.1	127.5	0.718	0.280	641	128.1	0.719	0.280	**0.001**	0.2	-0.5	0.001	0	0.001
	670	640.8	134.7	0.717	0.281	640.5	135.3	0.719	0.281	**0.001**	0.3	-0.5	0.002	0	0.002
	672	640.8	134.7	0.716	0.281	640.5	135.7	0.718	0.281	**0.002**	0.3	-0.7	0.002	0	0.002
	632	623.7	10.4	0.698	0.302	622.7	10.4	0.696	0.303	**0.006**	0.9	0	-0.002	0.002	0.003
	632	624.2	55.8	0.699	0.301	622.9	56	0.697	0.303	**0.005**	1.4	-0.4	-0.002	0.002	0.003
	633	624	110.7	0.699	0.301	623.2	110.9	0.697	0.302	**0.004**	0.7	-0.2	-0.002	0.001	0.002
	635	624.4	209.8	0.700	0.300	623.8	210.3	0.698	0.301	**0.003**	0.6	-0.2	-0.001	0.001	0.002
RED	636	624.7	291.7	0.700	0.300	624.5	292.5	0.699	0.300	**0.001**	0.2	-0.2	-0.001	0.000	0.001
	638	624.9	353	0.700	0.300	625.2	353.6	0.700	0.299	**0.000**	-0.3	-0.2	0	-0.000	0.000
	640	625	387.7	0.701	0.299	625.8	387.6	0.701	0.298	**0.002**	-0.8	0	0.001	-0.001	0.002
	643	625	391.2	0.701	0.299	626.5	388.3	0.703	0.297	**0.003**	-1.5	0.7	0.002	-0.002	0.003
	645	625.1	371.3	0.701	0.299	626.8	370.7	0.703	0.297	**0.004**	-1.7	0.2	0.002	-0.003	0.003
	621	616.4	10.8	0.683	0.316	614.7	11	0.679	0.321	**0.016**	1.7	-1	-0.004	0.004	0.006
	622	615.5	57.8	0.681	0.319	615.3	57.8	0.681	0.319	**0.013**	0.2	-0.1	-0.000	0.001	0.001
	623	616.4	110.8	0.683	0.316	615.9	111.1	0.682	0.318	**0.011**	0.5	-0.3	-0.001	0.001	0.002
	625	617.4	196.9	0.686	0.314	617.2	197.3	0.685	0.315	**0.007**	0.2	-0.2	-0.001	0.001	0.001
RED-ORANGE	627	618.4	252.3	0.688	0.312	618.4	252.5	0.688	0.312	**0.003**	0	-0.1	0	0	0
	630	619.4	273.4	0.690	0.310	619.6	274.1	0.690	0.309	**0.001**	-0.2	-0.2	0.001	-0.001	0.001
	633	620	266.7	0.691	0.308	620.9	264.8	0.693	0.307	**0.005**	-1	0.7	0.002	-0.002	0.003
	636	620.7	231.8	0.693	0.307	622.3	228.8	0.695	0.304	**0.008**	-1.6	1.3	0.003	-0.003	0.004
	638	621.2	204.7	0.694	0.306	623	202.9	0.697	0.303	**0.010**	-1.7	0.9	0.003	-0.003	0.005
	594	591.3	9.2	0.584	0.417	591.4	9.3	0.583	0.416	**0.043**	-0.1	-1.5	-0.001	-0.001	0.002
	594	592.2	50.1	0.587	0.412	592.1	51.4	0.587	0.412	**0.038**	0.1	-2.5	-0.001	0.001	0.001
	595	593.1	93.3	0.592	0.406	592.8	95.6	0.591	0.408	**0.032**	0.3	-2.4	-0.001	0.002	0.002
	597	594.2	152.6	0.599	0.400	594.4	154.1	0.600	0.399	**0.020**	-0.2	-0.9	0.001	-0.001	0.001
AMBER	599	596.3	183.1	0.609	0.390	596.1	178.2	0.608	0.391	**0.008**	0.2	2.7	-0.001	0.001	0.001
	602	597.7	178.2	0.616	0.383	597.7	178.4	0.616	0.383	**0.004**	-0.1	-0.1	0.000	-0.000	0.000
	604	599.9	163.2	0.625	0.373	599.6	161.3	0.625	0.375	**0.016**	0.3	1.2	-0.001	0.002	0.002
	607	601.8	138.7	0.635	0.365	601.3	139.3	0.633	0.367	**0.027**	0.5	-0.4	-0.002	0.002	0.003
	608	602.8	128.8	0.639	0.360	602.2	128.4	0.636	0.363	**0.032**	0.6	0.4	-0.002	0.003	0.004

Table 1, Part B

Tristimulus System vs. Reference Measurement Agreement (xy), cont.															
	LED	Camera				Reference					Result				
	Peak Wv (nm)	Dom. Wv (nm)	Lv	x	y	Dom. Wv (nm)	Lv	x	y	Δxy from Cal. Point	ΔDom. Wv (nm)	ΔLv (%)	Δx	Δy	Δxy
GREEN	534	541.7	39.2	0.247	0.721	541.6	42.7	0.248	0.717	**0.056**	0.1	-0.3	0.000	-0.003	0.003
	530	537.8	195.2	0.223	0.731	537.7	203.3	0.223	0.729	**0.034**	0.1	-0.4	0	-0.002	0.002
	528	535.6	358.3	0.211	0.733	535.5	370.1	0.211	0.732	**0.024**	0.1	-0.3	0	-0.002	0.002
	526	533.2	619.9	0.199	0.731	533.1	638	0.199	0.731	**0.014**	0	-0.4	0.000	-0.001	0.001
	525	531.7	821.9	0.194	0.725	531.7	845.6	0.193	0.726	**0.007**	0	-0.3	0.000	-0.001	0.001
	524	530.8	981.6	0.192	0.717	530.8	1003.8	0.192	0.718	**0.001**	0	-0.1	0.000	-0.000	0.000
	524	530.2	1104.7	0.192	0.709	530.3	1132	0.192	0.710	**0.009**	-0.1	0	0.001	-0.000	0.001
	525	530	1201.7	0.194	0.701	530	1228.2	0.193	0.702	**0.018**	0	0.3	0.000	-0.001	0.001
	525	529.9	1238.7	0.196	0.696	529.9	1263.3	0.195	0.697	**0.023**	0	0.4	0.000	-0.001	0.001
CYAN	510	513.4	37.1	0.093	0.701	513.4	38	0.094	0.699	**0.110**	0	-0.9	0.001	-0.002	0.002
	508	510.4	150	0.084	0.666	510.5	153	0.084	0.666	**0.076**	0	-0.7	0.001	-0.000	0.001
	506	508.8	255.4	0.081	0.643	508.8	260.3	0.081	0.643	**0.054**	0	-0.6	0.001	0	0.001
	505	507.1	418.2	0.080	0.615	507.2	425.2	0.080	0.616	**0.027**	-0.1	-0.4	0.001	0.000	0.001
	505	506.3	544.8	0.083	0.600	506.3	554.2	0.082	0.600	**0.011**	-0.1	-0.3	0.001	0.000	0.001
	505	505.9	649.4	0.086	0.590	505.9	659.5	0.085	0.589	**0.001**	0	-0.1	0.000	-0.000	0.000
	505	505.8	735.7	0.090	0.584	505.7	747.7	0.089	0.583	**0.008**	0	-0.2	-0.000	-0.000	0.000
	506	505.8	811.1	0.094	0.579	505.7	823.1	0.093	0.578	**0.014**	0.1	-0.1	-0.000	-0.001	0.001
	506	505.9	843	0.097	0.578	505.8	856.1	0.095	0.577	**0.016**	0.1	-0.2	-0.001	-0.001	0.001
BLUE	473	475.5	12.6	0.116	0.099	475.4	12.5	0.116	0.099	**0.011**	0.1	1.2	0.000	-0.001	0.001
	471	473.9	56.6	0.121	0.088	473.8	56.6	0.121	0.087	**0.003**	0.1	0.6	0	-0.001	0.001
	470	473.1	102.6	0.123	0.083	473.1	103.1	0.123	0.083	**0.007**	0	0.1	-0.000	-0.000	0.000
	470	472.8	185.2	0.124	0.082	472.8	186.1	0.124	0.081	**0.008**	0	-0.4	-0.000	0	0.000
	471	473.2	264.9	0.124	0.085	473.2	266.5	0.124	0.084	**0.004**	0	-0.6	-0.000	0.000	0.000
	472	474	346.4	0.122	0.091	474	347.9	0.123	0.090	**0.001**	0	-0.3	-0.000	0.000	0.000
	473	474.9	427.3	0.120	0.098	474.9	429.8	0.121	0.097	**0.009**	0	-0.3	0.000	0.000	0.000
	474	475.8	504.3	0.119	0.105	475.7	507.6	0.119	0.104	**0.016**	0	0	0.000	-0.000	0.000
	474	476.2	539.7	0.118	0.109	476.2	543.2	0.118	0.108	**0.020**	0	0	0.000	-0.000	0.000
ROYAL BLUE	451	454.1	4.1	0.153	0.024	454.2	4.2	0.153	0.024	**0.001**	-0.1	-1.4	-0.000	0.000	0.000
	451	453.8	21.6	0.154	0.023	453.8	21.8	0.154	0.023	**0.001**	0	-0.6	0	0.000	0.000
	450	453.6	42.2	0.154	0.023	453.6	42.5	0.154	0.023	**0.002**	0	-0.5	0	0	0
	450	453.7	81.2	0.154	0.024	453.7	81.7	0.154	0.023	**0.001**	0	-0.6	0	0	0
	451	454.1	118.4	0.153	0.024	454.1	119.1	0.154	0.024	**0.001**	0	-0.6	0	0	0
	451	454.6	154.2	0.153	0.025	454.6	155.1	0.153	0.025	**0.000**	-0.1	-0.3	-0.000	0	0.000
	452	455.2	187.9	0.152	0.026	455.2	189.1	0.153	0.026	**0.001**	0	-0.3	0	0	0
	452	455.9	220	0.152	0.027	455.9	221.5	0.152	0.027	**0.003**	0	-0.1	0	0	0
	453	456.4	235.3	0.151	0.028	456.4	237.1	0.151	0.028	**0.004**	0	-0.1	0	0	0

Table 1, Part C

	Tristimulus System vs. Reference Measurement Agreement (xy), cont.										
	Camera			Reference				Result			
	Lv	x	y	Lv	x	y	∆xy from Cal. Point	∆Lv (%)	∆x	∆y	∆xy
WHITE (2700K)	29.4	0.462	0.411	29.2	0.460	0.412	**0.067**	0.5	-0.002	0.001	0.002
	149.3	0.462	0.414	148.5	0.46	0.414	**0.068**	0.6	-0.002	0.000	0.002
	287.2	0.460	0.414	285.7	0.459	0.415	**0.067**	0.5	-0.002	0.001	0.002
	534	0.457	0.414	530.9	0.456	0.414	**0.064**	0.6	-0.001	0.000	0.002
	747.6	0.454	0.413	743	0.453	0.413	**0.061**	0.6	-0.001	0.000	0.001
	930.9	0.451	0.411	924.3	0.450	0.411	**0.057**	0.7	-0.001	0.000	0.001
	1078.6	0.448	0.410	1071	0.447	0.410	**0.054**	0.7	-0.001	0.000	0.001
	1191.7	0.445	0.408	1182	0.444	0.408	**0.050**	0.8	-0.001	0.000	0.001
	1230.4	0.443	0.407	1220.1	0.442	0.407	**0.048**	0.8	-0.001	0	0.001
	1253.6	0.441	0.407	1243.1	0.440	0.407	**0.047**	0.8	-0.001	-0.000	0.001
WHITE (3500K)	33.4	0.412	0.404	33.1	0.410	0.405	**0.020**	1	-0.001	0.000	0.001
	162.6	0.410	0.402	161.1	0.408	0.403	**0.017**	0.9	-0.001	0.000	0.001
	307.7	0.408	0.400	304.9	0.406	0.401	**0.014**	0.9	-0.001	0.000	0.001
	562.2	0.404	0.397	556.9	0.403	0.397	**0.009**	0.9	-0.001	0.000	0.001
	777.1	0.400	0.394	769.6	0.399	0.394	**0.004**	1	-0.001	0.000	0.001
	955.1	0.397	0.390	945.1	0.396	0.391	**0.001**	1.1	-0.001	0.000	0.001
	1091.3	0.393	0.388	1079.8	0.393	0.388	**0.005**	1.1	-0.001	0	0.001
	1185.4	0.390	0.385	1172.2	0.389	0.384	**0.010**	1.1	-0.001	-0.000	0.001
	1213.8	0.387	0.383	1200.1	0.387	0.383	**0.013**	1.1	-0.000	-0.000	0.000
	1228.7	0.385	0.382	1214.7	0.385	0.381	**0.015**	1.2	-0.000	-0.000	0.000
WHITE (5700K)	37.9	0.336	0.357	37.3	0.334	0.356	**0.071**	1.7	-0.002	-0.000	0.002
	187.1	0.335	0.353	184.2	0.333	0.353	**0.074**	1.6	-0.002	-0.000	0.002
	357.8	0.334	0.351	352.4	0.331	0.350	**0.077**	1.5	-0.003	-0.000	0.003
	664.4	0.331	0.347	654.3	0.328	0.346	**0.082**	1.5	-0.003	-0.000	0.003
	930.6	0.328	0.344	916.2	0.325	0.343	**0.086**	1.6	-0.002	-0.001	0.003
	1158.6	0.325	0.340	1139.4	0.322	0.340	**0.09**	1.7	-0.002	-0.001	0.003
	1341	0.321	0.337	1319.1	0.319	0.337	**0.095**	1.7	-0.002	-0.001	0.002
	1476.7	0.317	0.334	1451.7	0.315	0.333	**0.100**	1.7	-0.002	-0.001	0.002
	1523.3	0.314	0.332	1497.4	0.312	0.331	**0.103**	1.7	-0.002	-0.001	0.002
	1551.7	0.312	0.330	1525	0.310	0.329	**0.106**	1.7	-0.002	-0.001	0.002

The Importance of Measurement Accuracy: Pixel-Level Resolution

As noted previously, microLED sizes range from less than 100 µm to as small as 3 µm—about 1/10th the width of a human hair.[6] Measurement accuracy within the small area of an individual microLED depends on high imaging system resolution. To increase yields through display correction, it is essential to be able to isolate and measure each individual microLED emitter with precision so defects and luminance or chromaticity values specific to a given microLED can be corrected. A high-resolution imaging system optimizes the number of photo-sensing elements (sensor pixels) applied across each microLED and offers sufficient resolution to ensure all microLEDs in the display can be measured at once to complete correction processes within adequate takt times.

A microLED panel is composed of millions of pixels in chip form that are typically grown on 4- to 8-inch wafers. Each pixel contains some combination of red, green, and/or blue subpixels. To fabricate a display, each microLED chip (pixel) must be transferred to a substrate or backplane (panel) that holds the array of units in place. Measurement is typically performed during microLED production at the wafer level and the panel level.

General visual performance standards in the display industry allow for less than 10 dead pixels per display, thus epitaxial yield must be very high. Each microLED on the wafer must be measured to determine uniformity, verify individual distribution of dies, and measure luminance across red, green, blue, and occasionally white microLEDs. Once wafers have been deposited onto a backplane, manufacturers then need to verify overall uniformity of luminance and color distribution across the entire panel.

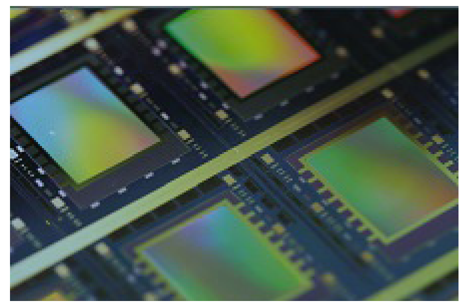
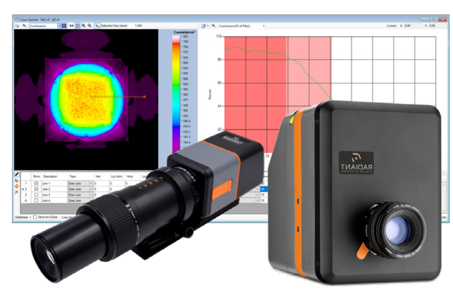


Image © JBD

Close up image of a microLED wafer.

The first step in ensuring microLED display quality is inspection and measurement at the LED, chip, and wafer stage to reduce the possibility of dead pixels and ensure luminance and wavelength (chromaticity) uniformity.

Wafer-Level Measurement. For inspection of microLED wafers, manufacturers must assess performance at the individual subpixel (microLED) level. A high-resolution, low-noise imaging colorimeter with a standard lens or microscope lens option can be used for this process. A microscope lens provides objective measurement with, for example, 5X or 10X zoom (5 to 10 times the effective resolution of the imaging system applied over an area of the device), allowing detailed measurement of each individual emissive element (Figure 9).



Radiant ProMetric Imaging Photometer or Colorimeter, the Radiant Microscope Lens (shown here attached to a ProMetric Y Photometer) and TrueTest™ Software are the components of an effective microLED measurement solution.

When used with a high-resolution imaging system, a microscope lens enables every display pixel to be captured over multiple sensor pixels for increased measurement precision. This type of system is effective for evaluation of display subpixels and characterization of individual microLEDs.

Panel-Level Measurement

Once individual microLED chips are transferred onto a backplane, an imaging colorimeter with standard lens can be used to measure luminance and color uniformity across an entire panel. The advantage of an imaging colorimeter is its ability to capture a large area in a single image to detect and measure non-uniformity quickly and accurately, just as a user would view a display.

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High-resolution imaging systems can continue to provide pixel- and subpixel-level measurements at the panel level to enable correction. To assess luminance, chromaticity or uniformity at this stage, manufacturers need accurate data at each display pixel's coordinate position, which can then be downloaded into a coefficient calculator to determine and apply factors for display uniformity correction. This process increases the demand for imaging accuracy at the panel level, even for very high-resolution imaging systems. Measurement systems that use tristimulus filter wheels maximize resolution by combining multiple images (one for each color channel) for a single measurement, each image at full-sensor resolution (see Figure 5, above).

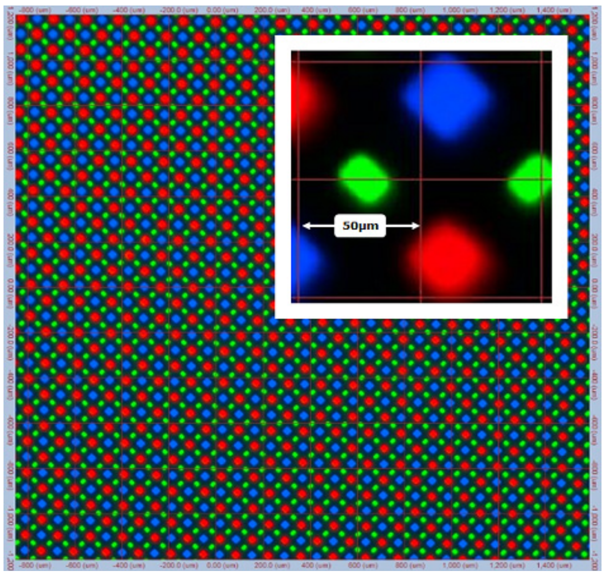

Figure 9 - *Example of subpixel measurement (main image) taken by a Radiant ProMetric Imaging Colorimeter and a Radiant Microscope Lens magnified to show 50 µm distance at 10X zoom (inset image).*

Methods to Improve Pixel Registration and Measurement

The demura method has been proven effective for ensuring the visual quality of millions of OLED displays in mass production worldwide. However, microLEDs offer the potential to increase display resolution and pixel pitch exponentially, requiring new approaches to continue to achieve accurate measurement (demura Step 1) and correction (Steps 2 and 3).

Accurate pixel-level measurement relies on a measurement system's ability to sufficiently isolate each pixel and precisely quantify its output value. As described above, imaging system resolution determines the number of photo-sensing elements (sensor pixels) available to cover each individual display pixel. Applying more sensor pixels per display pixel increases the granularity of data acquired by the imaging system for accurate pixel registration and measurement. As overall display resolution increases, an imaging system's ability to apply sufficient sensor pixels per display pixel—while continuing to capture measurements for all display pixels in a single image to ensure efficiency—is reduced.

Radiant has developed two methods that have been proven to significantly improve an imaging system's ability to isolate and measure subpixels of increasingly high-resolution displays: a "spaced pixel" method and a "fractional pixel" method, described below.

Spaced Pixel Method

The spaced pixel measurement method (US Patent 9135851) improves the effective resolution by applying a measurement system's total image sensor resolution across only a subset of display pixels at one time. For this method, testing software employs a series of dot-matrix test patterns shown on the display screen as part of a measurement sequence. Each pattern illuminates a subset of the display's subpixels, while the rest are turned off (Figure 10). An imaging system measures the output (luminance or chromaticity) of the "on" pixels for each pattern. A subsequent test image adjusts the matrix to turn off the first set of pixels and turn on the next set of pixels for measurement. This process is repeated until all pixels in the display are measured.

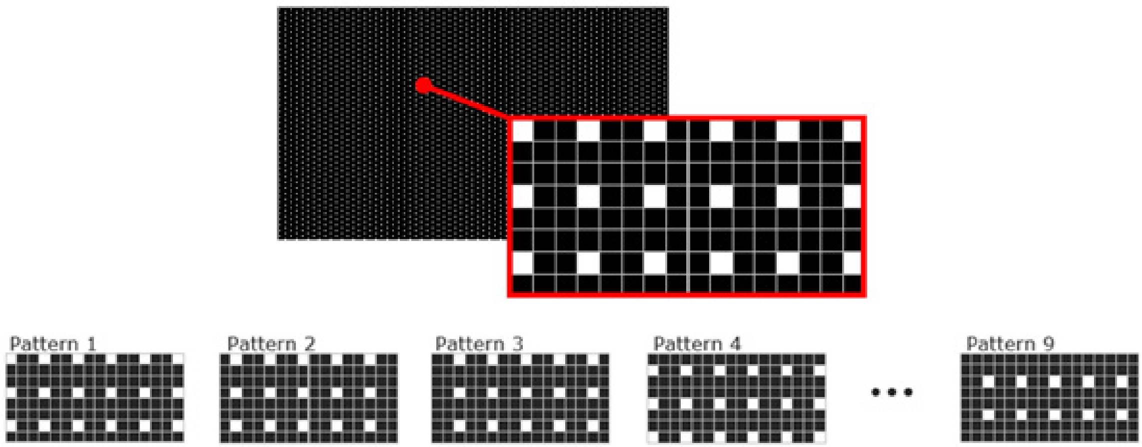

Figure 9 - *During spaced pixel measurement, a series of dot-matrix patterns illuminates sets of pixels until values have been acquired for all pixels in the display.*

This process increases the effective resolution of the measurement at each display pixel, ensuring the isolation of each pixel's output, and thus the accuracy of measurement calculations across displays of any arbitrary resolution. Images from the spaced pixel measurement method are combined into a single, synthetic image for analysis, which compares values at each of the pixel's x,y coordinate locations to determine uniformity. The software calculates the necessary correction coefficient for each display pixel and applies the correction at each pixel's coordinate location to adjust values until the display is uniform.

The spaced pixel method reduces the requirement for measurement resolution of an image-based system to increase measurement accuracy. However, because this method requires multiple images, takt times are also increased. By comparison, the fractional pixel method (explained in the next section) improves measurement accuracy without increasing takt times. For example, using the fractional pixel method only a single image is required to measure typical smartphone displays. Thus, the fractional pixel method offers advantages when shorter takt times are required, as in many production-level test and correction applications.

Fractional Pixel Method

The fractional pixel method (US Patent 10971044) addresses measurement scenarios where imaging sensor resolution per display pixel is limited, enabling measurement systems with standard resolution to continue to accurately measure and correct today's high-resolution displays, even in a single-image measurement of the entire display.

First, the fractional pixel method optimizes pixel registration. Pixel registration is a method of dynamically locating and setting a region of interest (ROI) around each pixel in the measurement image. In traditional measurement methods, ROI are aligned to the imaging system's sensor pixel array. However, as display resolutions continue to increase relative to measurement system resolutions, it is more likely that the center of a display pixel will not be aligned with the center of a sensor pixel, thereby reducing the ability of the ROI to precisely cover and isolate each display pixel. This misalignment can result in measurement error. By comparison, the fractional pixel method sets a registration area around each display pixel using a floating point, aligning this ROI to the center of a display pixel based on the highest measured luminance across the pixel.

Second, the fractional pixel method optimizes pixel measurement. The fractional pixel method calculates pixel values based on the fractional area of each sensor pixel contained within the ROI (see Figure 11, right image). This improves the precision of measured values over traditional "whole pixel" methods that factor values from the whole area of sensor pixels contained partially within the ROI (see Figure 11, left image). The fractional pixel method ensures the accuracy of pixel-level measurements for extremely high-resolution emissive displays beyond what was previously possible using a single-image capture. With the fractional pixel method, imaging systems with limited resolution (relative to display resolution) can continue to effectively measure pixel-level values across a display in a single image, thus increasing takt time without reducing measurement accuracy.

First, the fractional pixel method optimizes pixel registration. Then it optimizes pixel measurement, ensuring the accuracy of pixel-level measurements for emissive displays of much higher resolution than was previously possible using a single-image capture, to increase takt time.

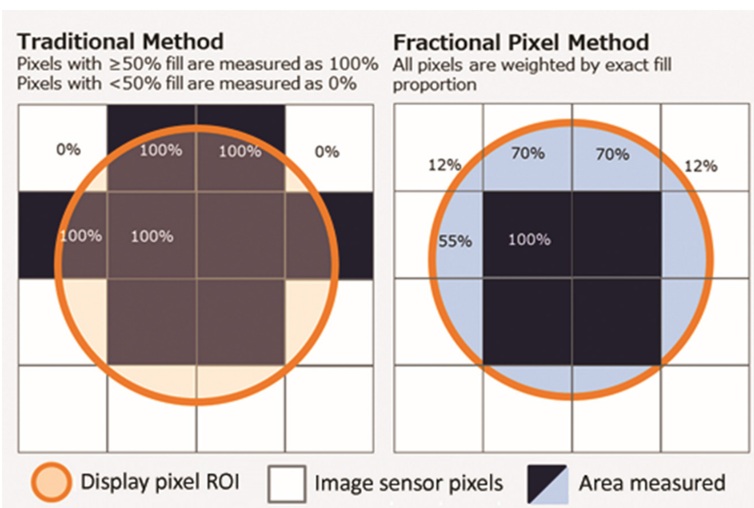

Figure 11 - *Illustration of a traditional whole pixel measurement method versus the fractional pixel method. In the traditional method (left), display pixels are measured using 100% of the data from sensor pixels whose area is more than 50% inside the ROI, and 0% of the data from sensor pixels whose area is less than 50% inside the ROI. Using the fractional pixel method (right), display pixels are measured using a percentage of data based on the percentage of sensor pixel area inside the ROI*

Full details on the study of fractional pixel method of measurement and correction can be found in: Pedeville, G., Rouse, J., and Kreysar, D., "Fractional Pixel Method for Improved Pixel-Level Measurement and Correction (Demura) of High-Resolution Displays," Society for Information Display (SID) Display Week 2020 Digest. Book 2, August 2020.

Measurement Accuracy Study: The Fractional Pixel Method

The accuracy of the fractional pixel method was demonstrated in a study published by Pedeville, Rouse, and Kreysar (2020).[7] Figure 12 plots single-image measurement data from this study, comparing the pixel-level measurement accuracy of fractional pixel measurements, whole pixel measurements, and extremely high-resolution reference measurements. The fractional pixel data adheres closely to the reference data, whereas the whole pixel measurements diverge from the reference data at multiple points. Figure 13 shows the before-and-after result of an actual demura application using a 43MP ProMetric Imaging Photometer system employing both spaced and fractional pixel methods to correct a microLED microdisplay panel.

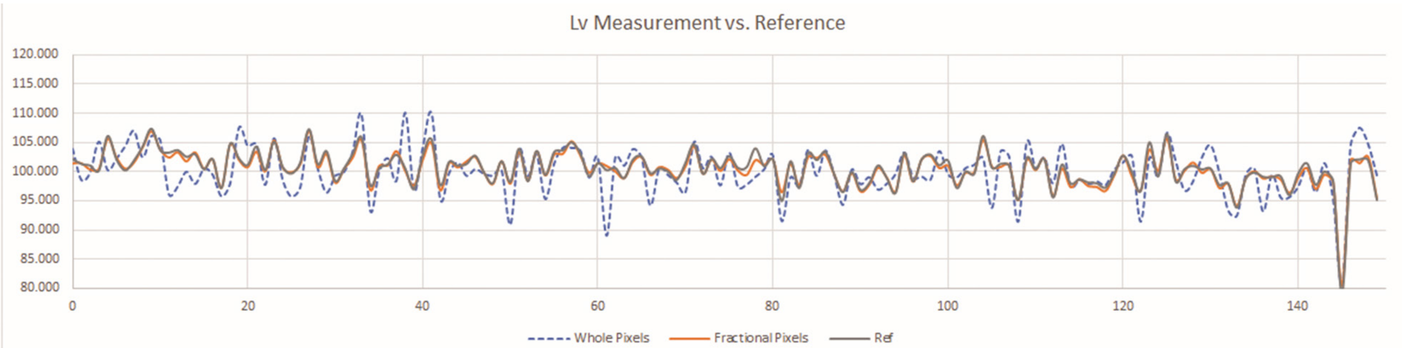

Figure 12 - *Normalized luminance (Lv) measured by whole and fractional pixel measurement methods (achieving 3.2 x 3.2 sensor pixels per display pixel) and reference luminance (achieving 30 x 30 sensor pixels per display pixel) for the same row of display pixels.*

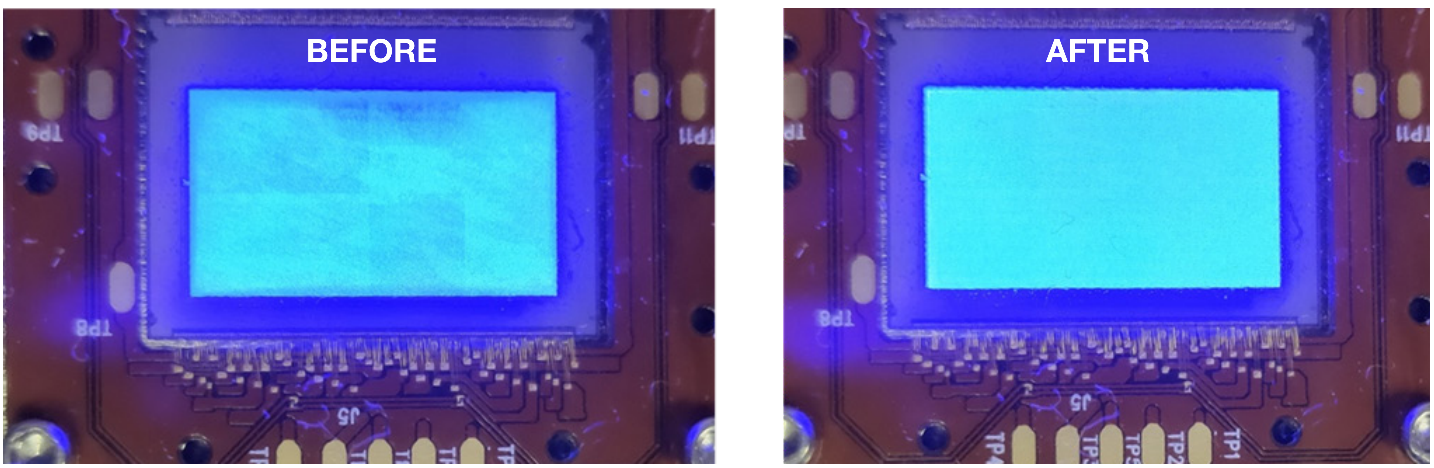

Figure 13 - *MicroLED microdisplay panel shown before (left) and after (right) demura correction. The panel shown is 0.7" with full HD, 1920 x 1080, LED size/pitch of 2 µm / 8 µm. Measurement and correction performed using a ProMetric Y29 Imaging Photometer with microscope objective lens and TrueTest™ Software.*

Conclusions

MicroLED displays are quickly taking their place in the highly competitive consumer device marketplace. Developers are racing to find production solutions that deliver performance and exceed customer expectations, while maintaining cost-effective processes and high yields.

Defects, variations in color or brightness, and other irregularities can quickly deflate buyer satisfaction, hurt brand reputation, and erode market share. If these issues cannot be addressed and corrected at the component level, low yields and high production costs will impede the viability of microLED display technologies for mass production and market commercialization.

High-resolution tristimulus imaging colorimeter systems provide an efficient quality control solution to support production benchmarks for microLED displays. These systems rely on their color filter method, calibrations, and subpixel measurement capabilities to ensure accurate data is captured at the pixel and subpixel level, thus enabling display correction that increases yields and safeguards manufacturing resources.

Studies of recent display metrology systems and methods demonstrate the effectiveness of high-resolution tristimulus imaging systems—combined with sophisticated algorithms for calibration, registration, and measurement—to solve microLED display luminance and color uniformity challenges and support the viability of microLED technology for the display device marketplace.

Using imaging colorimeters and novel correction methods, microLED wafer, panel, and device manufacturers have a solution for production efficiency that enables them to ensure quality, reduce waste, and continue to innovate high-performance displays in a range of types, sizes, and applications.

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Emissive display types such as OLED and microLED offer visual appeal and performance, but the individual emitters can exhibit variable luminance and chromaticity, creating a non-uniform appearance. This paper presents solutions for precision measurement and correction of microLED displays that are helping manufacturers improve visual quality and increase production yields.

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