How to Use Imaging Colorimeters to Improve OLED Display Production Testing Efficiency and Yields
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Introduction
OLEDs (Organic Light-Emitting Diodes) are emerging as the next wave of technology in the flat-panel display market. This is exciting because OLED displays promise improved display appearance for both smartphones and large-format TVs at lower cost and power than other display technologies. OLEDs have superior contrast ratios and sharper images with deeper blacks and more vibrant colors. They require no backlight, resulting in a thinner, lighter-weight display that uses less electricity. OLEDs also bring a dramatic boost in responsiveness, about 1,000 times faster than existing technologies, virtually eliminating blur on fast-moving and 3D video.

As OLED manufacturers work to launch commercially viable OLED-based products, high costs due to material prices and manufacturing yield issues have hindered widespread OLED technology adoption, most dramatically in large-format implementations, as they drive up end-customer prices. The smartphone market has been the most successful segment for OLED technology to date and will likely be the catalyst that drives long-term adoption of OLEDs for other applications. Display Supply Chain Consultants (DSCC) cites smartphones as the dominant OLED market, accounting for around 91% of units per year with revenue share around 79% by 2022. This growth requires improvements in manufacturing efficiency.

![Figure 1 - Smartphone market leads the way for OLED adoption. [Source: DSCC's Quarterly OLED Shipment and Fab Utilization Report]](image)

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For the large-format OLED TVs, although the short-term market size is small, analysts at DSCC predict that TVs will take second seat to smartphones, rising to 42% market share by 2022, and overtaking LCDs by 2021. However, manufacturers have found it difficult to achieve consistent picture quality on large-format OLED displays, resulting in low production yields. This impacts the timing of viable market entry and drives up retail prices for OLED large-screen TVs. Current large screen OLED TVs are priced into the thousands of dollars (USD), making lower-cost, high-definition LCD and LED options more appealing to the wallets of budget-minded consumers; the price point for volume market adoption of OLED and replacement of current technologies will be significantly lower.

OLED Manufacturing Challenges

OLED technology adds several unique challenges to the manufacturing process, regardless of the size of display.

**Line Mura**

In the OLED manufacturing process, material is deposited on a substrate to form the individual sub-pixels. If this process is not completely uniform, the end result may be line mura, which appears as well-defined horizontal and/or vertical orientation in the OLED display.

![Figure 2 - OLED display with uncorrected line mura.](image)

**Sub-Pixel Luminance Performance**

OLEDs use organic semiconductor material that is emissive, meaning it lights up when electric current is applied. Because of this, OLED and other emissive displays (like LED and emerging microLED) do not require a backlight. OLED display pixels are composed of red, green, and blue sub-pixels. The output of each sub-pixel is individually controlled. Brightness (luminance) and color are determined at the pixel level by combining the sub-pixel outputs. Due to production discrepancies, there may be variations in luminance for the same electrical signal input throughout the population of same-colored sub-pixels on the display. This results in differences in brightness from pixel to pixel.
Figure 3 - Sub-pixels combine to create pixels with various colors and brightness.

This sub-pixel-level variability in OLED and other emissive displays results in different performance issues than those that occur in LCDs. In LCD panels, adjacent pixels generally have the same luminance because LCDs use a common backlight, so the brightness of adjacent pixels will be fairly uniform.

Display Color Non-Uniformity
A second impact of inconsistent brightness levels of the OLED display sub-pixels is reduced color accuracy and color non-uniformity across the display. To achieve accurate and uniform colors, the brightness of each individual sub-pixel must be tightly controlled. The reality is that even within a well-controlled manufacturing process, sub-pixels in OLED and other emissive displays will have significant variations in brightness levels. When these variations are not compensated for, there may be non-uniformity of color across the display, reducing picture quality to potentially unacceptable levels and so reducing production yields.

Ideal “White” Pixel

Uncorrected “White” Pixel

Green OLED brightness is 10% too low

Figure 4 - Incorrect brightness levels create non-uniformity in color across an OLED display.
Imaging Colorimeter Applications to OLED and Other Emissive Display Manufacturing

Imaging colorimetry-based display test systems have demonstrated success in improving quality and reducing production costs for both LCD and LED display screens. Testing applications span smartphones, tablets, laptops, monitors, TVs, and digital billboards. These proven techniques can be adapted to OLED and other emissive display production testing as well, enabling manufacturers to incorporate this technology into the same devices with the same positive return on investment.

The two key components of a display test system are:

1. **Imaging Colorimeters**, which provide accurate measurement of display visual performance that matches human perception of brightness, color, and spatial (or angular) relationships. High-performance imaging colorimeters can accurately measure the luminance (brightness) of individual sub-pixels in an emissive display like OLED as well as overall display uniformity.

2. **Test Execution and Analysis Software**, which is production-line software for image analysis to identify defects and quality issues, quantify their magnitude, and assess the measurements to make pass/fail determinations. This software can also include display performance correction methods that can be adapted to identify and correct variations that are unique to emissive displays.

Improving Delivered Quality to Enhance Customer Experience

In a typical manufacturing process, display visual performance is tested by human inspectors, resulting in high variability in the quality of delivered product. With the improved image quality of OLED displays, this is becoming an even more significant issue. Human inspectors are not able to consistently and repeatably evaluate display quality on high-contrast, high-resolution displays.

Automated visual inspection (AVI) using imaging colorimeters has multiple benefits, which improve quality control for the manufacturer and user experience for the consumer:

- Improved consistency in test application—from line to line and location to location—as all systems share the same calibration and test definitions
- Quantitative assessment of defects, with precise filtering of good from bad (pass/fail)
- Increased testing speed, which allows more tests to be run in the same time interval, increasing throughput while ensuring a more careful assessment and a better end product
- Simultaneous assessment of full-display quality (e.g., to check uniformity and color accuracy) and fine-scale (e.g., pixel- and sub-pixel-level) defects

When applied in OLED display testing, imaging colorimeter-based AVI simplifies testing while improving delivered product quality and production expense.
Correcting OLED 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, or electronic compensation, to improve display quality. The concept is simple: by modifying the inputs to individual sub-pixels of an emissive display, previously-identified dim sub-pixels can be brightened resulting in improved luminance uniformity and correct color across the display.

Performing electronic compensation for OLED displays requires, first, having in-display electronics that can accurately control brightness of the individual sub-pixels and adjust this based on a set of pixel-specific correction factors. Second, a system is required to accurately measure individual sub-pixel brightness and color, and compute specific correction factors for each of them. This method has been widely used for LED display screens made up of individual LEDs, and Radiant Vision Systems has adapted this technique to OLED and other emissive displays like microLED in a method called “demura.”

![Figure 5](image_url)

**Figure 5** - Results of the Radiant demura method for correction of emissive displays (like OLED, LED, and microLED), captured by a ProMetric® 29MP imaging system; before demura (left) and after (right).

The demura method employs three distinct steps:

1. **Measurement** of each sub-pixel in the display to calculate luminance values at each pixel location (performed on different test images to measure different display colors) using a high-resolution imaging colorimeter.
2. **Calculation of correction factors** needed to normalize luminance discrepancies between sub-pixels in the display using test analysis software.
3. **Application of correction factors** to the display signals using an external control IC (integrated circuit) system.

When an OLED display is completely assembled, test images can be displayed on screen to target output color values. These images enable measurements and calibration to be computed for each of these values. For example, a “green screen” with all green sub-pixels turned on can be used as a sample image and the imaging colorimeter can measure and record the brightness of each individual green sub-pixel. This is repeated for all the primary colors and, usually, white. This data can be gathered in the course of ordinary quality testing of the OLED display.
Calculating luminance values of each and every pixel in extremely pixel-dense OLED displays, however, can be challenging. For standard Full High Definition (FHD, 1920 x 1080 pixel) and lower-resolution displays, a single 29-megapixel imaging system offers sufficient resolution for testing. However, for higher-resolution displays (for example, Quad High Definition or QHD), even very high-resolution imaging systems may be unable to capture all pixels in a single image for complete analysis, especially for today’s increasingly-large displays. To overcome this challenge and adapt a measurement method for any arbitrary size and resolution of OLED display, Radiant’s demura method employs a measurement process that combines data from a Spaced Pixel Test Pattern analysis, a patented method (US Patent 9135851) that can be employed using a single photometric imaging system.

Pattern 1

Pattern 2

**Figure 6** - Example of the Spaced Pixel Test Pattern method of pixel-level luminance measurement for extremely high-resolution displays.

Using a Spaced Pixel Test Pattern, dot matrix patterns of pixels are illuminated at intervals and measured by the imaging system in multiple passes. Measurements are repeated for all dot-matrix patterns until each display pixel is analyzed in its illuminated state. When using a camera with higher resolution than the display itself, each display pixel can be tested over many CCD pixels, ensuring the highest accuracy of the associated pixel’s measured luminance value.

**Figure 7** - Each illuminated display pixel is automatically registered by the analysis software and defined within a region of interest (ROI). Because the imaging system resolution is much higher than the display resolution, each display pixel may be measured across an ROI captured by multiple CCD pixels.

Once all patterns of illuminated pixels have been analyzed, software combines all measurement images into a single “synthetic image” with the same resolution as

**Figure 8** – ROI are dynamically defined regardless of OLED pixel pentile structure, meaning that any arbitrary pixel pattern can be measured to apply demura to any display.
the measured display. This image depicts every display pixel in rows and columns, providing accurate x,y coordinates for each pixel and their associated luminance values. This step in the demura process enables accurate detection of defective pixels and their exact coordinates.

**Figure 9** - Software locates the defective pixels in the display using a synthetic image that combines the data from multiple high-resolution measurement images of the display.

Once these values are known, unique correction factors can be computed and applied to the electrical input of each individual sub-pixel, so that brightness will be accurate and uniform across the entire display across at gray levels. When this correction map is applied to the finished OLED display, there is a significant improvement in color & brightness accuracy and uniformity. The net effect of demura is that displays that would have failed quality inspection without electronic compensation will now be able to pass, thereby reducing waste and increasing production yield.

**Figure 10** - Captured images of a blue test screen on an OLED display before and after demura correction (shown using false color to illustrate luminance levels).

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Radiant Vision Systems Solutions

OLED technology is promising to be the next generation for flat-panel displays and especially curved displays, but technical issues related to image quality and production yields need to be resolved before OLED can be considered commercially viable beyond the smartphone market. The issues facing OLED manufacturers, although unique, are similar to technical issues that have already been solved by Radiant Vision Systems in LCD production and for LED screen manufacturers.

ProMetric® Imaging Colorimeters

Radiant Vision Systems ProMetric Imaging Colorimeters are high-sensitivity, high-accuracy, CCD-based imaging systems calibrated to match human visual perception of spatial and angular distributions of brightness (luminance) and color. Radiant Vision Systems offers 10 different models of imaging colorimeters—more than twice as many as anyone else in the industry—with multiple options for resolution and sensitivity. The appropriate system for specific display testing scenarios will depend on your desired measurement accuracy and resolution requirements.

TrueTest™ Software

Accurate measurement of OLED display performance is important, but an equally-important component is the analysis of the measurement data. Radiant Vision Systems TrueTest Automated Visual Inspection (AVI) Software completes the display test solution and makes data actionable by implementing test sequences against user-defined pass/fail criteria. TrueTest is a software test suite and sequencer with built-in tests available for display uniformity testing, line defect detection, pixel defect detection, contrast measurement, and more. TrueTest allows the user to select from a test library and order tests in any sequence for rapid analysis of multiple characteristics. The user can also specify test parameters and pass/fail criteria. TrueMURA™ is an add-on test suite module to TrueTest that adds JND (“just noticeable difference”) mura and blob analysis techniques.

TrueTest incorporates software alignment and moiré pattern removal functions to simplify test setup. On the production line it runs in Operator mode where access to test parameters is locked, preventing changes. TrueTest also stores configuration information, test parameters, and pass/fail criteria for multiple models of displays; the correct data file can be applied or changed on the fly during real-time production.

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Integration and Support

Practical implementation of the Radiant Vision Systems display test solution requires both physical and software integration in the production line. Radiant Vision Systems is experienced at working with customer-selected fixture providers, or providing full turnkey solutions that include fixtures. TrueTest software can operate in a standalone mode, but more typically it is integrated with the Production Control System (PCS) of a manufacturer’s line. This integration can provide fully-automated testing, wherein Radiant’s software is triggered by the PCS, or simply provides a reporting interface for pass/fail results (and potentially testing data). TrueTest can also be set up to work with video pattern generators and barcode readers (or the equivalent).

Radiant Vision Systems provides global support for all ProMetric and TrueTest solutions. Our support staff provides engineering, installation, training, maintenance, and calibration services. Radiant Vision Systems has support staff in the US, China, Japan, Korea, and Europe, supporting thousands of imaging colorimeters currently deployed on hundreds of production lines worldwide.

References
Imaging colorimetry-based display test systems have demonstrated success in improving quality and reducing production costs for LCD displays and LED display screens. Radiant Vision Systems has extended these proven techniques to production testing of other emissive displays like OLED and microLED. Contact us to learn more about “demura” display correction and how it can improve your production efficiency.