

WHITE PAPER

Methods for Measuring Display Defects and Mura as Correlated to Human Visual Perception



A Konica Minolta Company

Methods for Measuring Display Defects and Mura as Correlated to Human Visual Perception

Introduction

Human perception is the ultimate standard for assessing display quality. However, the use of human inspection as a metrology method in display evaluation for either development or production is problematic because of the statistical variation between observations and observers. Human vision is subjective, unquantifiable, and difficult to replicate. This imprecision makes it difficult to apply standards consistently from inspector to inspector. This has implications when comparing various display designs and technology, especially over time, within a development environment. In a production environment this variability also makes it particularly difficult to apply visual quality standards to multiple sources throughout a supply chain. This variability may increase the risk of accepting defective devices or failing good devices—both of which add cost to the manufacturing process. Human inspection also lacks detailed quantitative information about defect types and occurrences, especially since human observers tend to only classify the most obvious defects. What's more, displays have become the pivotal user interface in consumer devices, from televisions to smartphones to automotive interiors, so quality control measures that take human visual experience into account are particularly important in display manufacturing.

Visual display testing is rapidly being automated using photometric and colorimetric imaging systems that are capable of objectively quantifying visual qualities like brightness (luminance), color, and contrast of displays. These systems are also used to detect defects like stuck-on or stuck-off pixels, lines, and mura (a term used for non-uniform areas or blobs in a display). Imaging systems with light and color measurement capabilities (imaging colorimeters) can give spatial tolerances (size, position, location) to visual qualities of a display. An imaging colorimeter preserves the spatial relationship of measurements across the display, which is required for measuring spatial variations.

Currently, there are a number of commercial systems available that utilize imaging colorimeters to identify display non-uniformities in color and brightness, and discontinuities such as line and point defects. However, the problem of creating an automated system for the detection of more subtle defects that is well-matched to human perception has been more challenging. Until recently, it has been difficult to devise clear software algorithms for automated defect classification directly correlated to human perception. This is in part because human perception of noticeable differences across a display is dependent on contextual factors that indicate defect severity, and standard display defect analysis algorithms, (based on methods such as setting thresholds and edge detection), are not directly correlated to human perceptions in these cases.

Just Noticeable Difference

Recent advances in modeling human visual sensitivity to display defects have allowed the development of automated methods for detection of just noticeable differences (JND)



Human perception is the ultimate standard for assessing display quality. However, the use of human inspection as a metrology method in display evaluation is problematic because of between observations and observers.



Recent advances in modeling human visual sensitivity to display defects have allowed the development of automated methods for detection of just noticeable differences (JND) for displays.

for displays. Based on a sampling of human observers, the JND scale is defined so that a JND difference of 1 would be statistically “just noticeable” by an observer. On an absolute scale, a JND value of 0 represents no visible spatial contrast and an absolute JND value of 1 represents the first noticeable spatial contrast. For display technologies, this scale allows for the grading of display defects. By using a computer-controlled imaging colorimeter to capture data on spatial distribution of display luminance and color, and then analyzing the data to create a JND map of the image, mura defects in a display image can be graded with a direct correlation to human visual perception.

JND analyses are derived from a Spatial Standard Observer (SSO) software algorithm developed by NASA that incorporates a simple model of human visual sensitivity to spatial contrast.¹ The algorithm was specifically created for display metrology applications and the identification of display mura. This algorithm has been adapted for use in some image analysis software to identify and grade arbitrary display data captured by an imaging photometer or colorimeter. Factors that are included in this model are: spatial frequency (how fast spatial contrast varies), orientation (the angular orientation of the spatial contrast relative to the viewing plane defined by human eyes), and the observer’s distance from the display being viewed. In general, the analysis technique can be applied to either a photopic or colorimetric measurement image; because the analysis method generates useful data for both brightness and color, we will generally refer to colorimetric images.

Display defect detection performed using this type of system demonstrates that JND analysis is an effective means of obtaining additional information about display image quality that extends to other analysis techniques. This analysis system can be applied to any display type, including LCD, LED, and OLED displays.

A short synopsis of the SSO algorithm:

- The input to the algorithm is a pair of images: the test image and a reference image.
- The test image is the initial imaging colorimeter measurement, containing potential mura defects.
- The reference image is computed from the test image using a low-pass filter designed to eliminate the mura.
- The difference between test and reference images is filtered by a contrast sensitivity function (CSF).
 - The CSF is a measure of the visibility of different spatial frequencies at different orientations. It models the decline in human visual sensitivity at higher spatial frequencies and at very low frequencies, as well as the lower sensitivity at oblique orientations (the oblique effect).
- The filtered image is then multiplied by an aperture function.
 - The aperture function models the decline in human visual sensitivity with distance from the point of fixation.
- The final step is a non-linear pooling of the resulting image over space to produce the JND image.

Automated Measurement System Structure

Automated measurement and analysis of displays with an imaging colorimeter requires combination measurement control and analysis software. The general structure of the system that we have developed for this application is shown in Figure 1. The key components of the system are: (1) a scientific-grade imaging colorimetry system; (2) PC-based measurement control software which both controls the imaging colorimeter and test image display on the device under test; and (3) a suite of image analysis functions that allow various tests to be run, including JND analysis. The result is a system that can be easily automated for a variety of display defects and delivers quantitative results including point and line defects as well as JND analysis.

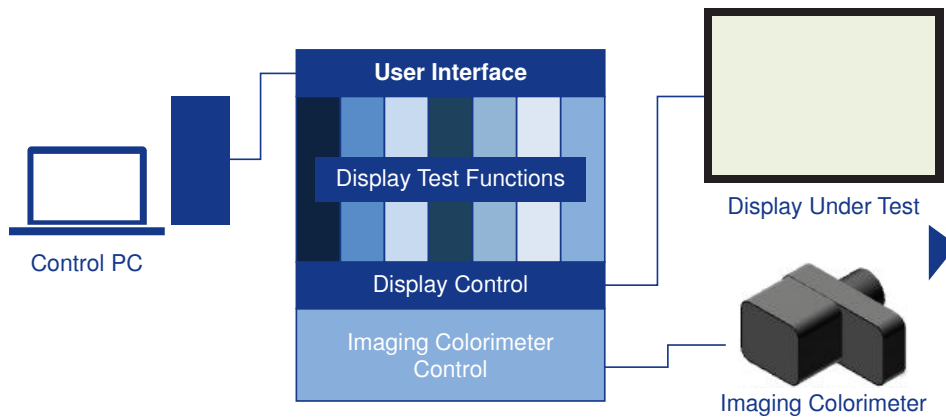


Figure 1. Structure of an automated display measurement system, which consists of an imaging colorimeter and measurement control and image analysis software. The user interface allows the selection and management of the display test functions, which, in turn drive the display and imaging colorimeter through control interfaces.

The software architecture used has a core set of measurement control modules that provide the interface to the imaging colorimeter and the display under test. A series of specific test functions is built on this base, using function calls to generate various measurements of white, red, blue, green (and other) display screens at various brightness settings for uniformity analysis, or of checkerboard patterns for contrast measurement. The software user interface allows test selection as well as specification of test parameters and pass/fail criteria where relevant. For production applications, the user interface supports both administrator mode (with full access to test specifications), and operator mode (which only allows test execution).

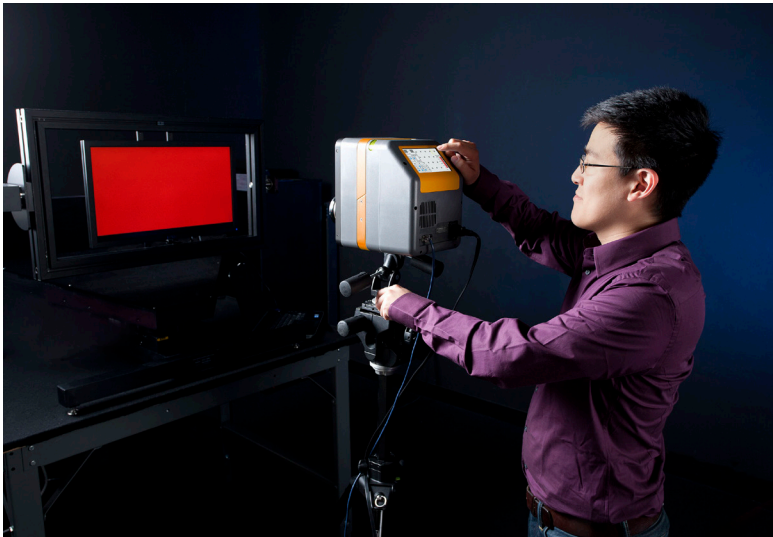
The Use of Imaging Colorimeters for Measuring Displays

The quality of the analysis of display mura is dependent on the quality of the data gathered by the imaging colorimeter. While such a system is conceptually simple, in practice careful attention must be paid to the design and calibration of the imaging colorimeter and to the measurement setup in order to yield accurate results. This is especially true for mura detection, although the standard image analysis algorithms for uniformity measurement, line defect detection, and point defect detection also require good input data as well as accurate data analysis to be meaningful.

Imaging Colorimeter System Design

The main components of an imaging colorimeter are an imaging lens, a set of color filters, an image sensor, and data acquisition and image processing hardware/software.² Other elements may include neutral density filters and a mechanical shutter. To perform colorimetric measurements, the system acquires an image of the device under test

through each of the various color filters. When needed, neutral density filters are employed to ensure that each color measurement uses the full dynamic range of the sensor. Photometric measurements are performed using only the green (photopic) filter.



The image data is then processed using previously-determined calibrations to yield accurate color or luminance data for every pixel in the image. The spatial resolution of this data depends upon the imaging system’s optics and sensor dimensions. The benefit of using an imaging colorimeter is that the luminance and color of every pixel in a display are measured simultaneously at a given view angle. The imaging colorimeter preserves the spatial relationship of measurements across the display, which is required for measuring spatial variations.

Because an imaging colorimeter acquires millions of data points in a single measurement, it is inherently a much faster inspection solution than an approach based on individual spot measurements. In addition, simultaneously measuring the entire surface of the device under test makes an imaging colorimeter useful for gauging overall color and luminance uniformity, identifying very small defects, and grading the severity of defects as observed within the display in whole. The imaging colorimeter can even be used to render a processed image of the display, which can help to reveal subtle features (mura) for quantitative analysis, such as defect severity or position trending.

Applications for Display Visual Performance Testing

The selection of an imaging colorimeter for specific display measurements will depend on display specifications, including pixel resolution and pitch, and measurement objectives, including whether uniformity alone, or additionally pixel-level defects, are to be measured. Imaging colorimeter attributes that can be selected include image sensor type, resolution (greater resolution is usually required to identify pixel or sub-pixel defects), dynamic range, field of view (which will be a function of image sensor and lens choice), and measurement speed (where faster measurement speed usually means lower measurement accuracy).

In the application of JND analysis for display defect detection described in this paper, a Radiant Vision Systems ProMetric I8 Imaging Colorimeter was used with measurement

Figure 2. A Radiant Vision Systems ProMetric® Imaging Colorimeter is the typical test and measurement equipment used for display defect detection. The imaging colorimeter technology and resolution are usually selected based on the display specifications and the array of tests to be performed. Most tests are performed with the display normal to the imaging colorimeter, but the display may be rotated with respect to imaging colorimeter to obtain view angle data, including for JND analysis. In an alternative configuration, a conoscope lens mounted directly to an imaging colorimeter can achieve similar results by simultaneously evaluating all angular distributions of light to in a single measurement.

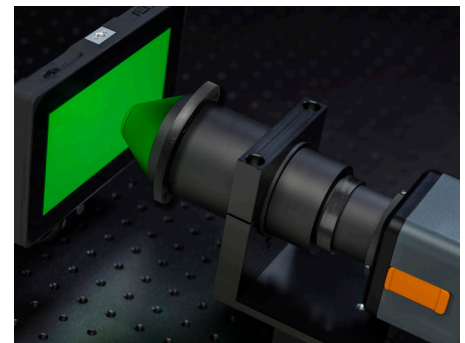


Figure 3. A Radiant Vision Systems FPD (Flat Panel Display) Conoscope Lens, uses Fourier optics to measure view angle performance of displays, including luminance, chromaticity, and contrast as seen from a range of angles.

control and test management functions performed by TrueMURA™ Software. This software manages a full range of the visual and quantitative tests for qualifying display performance, as well as performing tests in automated sequence for in-line inspection. TrueMURA Software includes tests for brightness and gamma correction, color correction, identification of general mura and pixel defects, brightness and color uniformity, contrast ratio, image quality, image size and location, convergence, and many other tests. For the study discussed in this paper, a JND analysis test function was incorporated.

Test Set-Up

Display testing must generally take place in a darkened environment, using a dark room or enclosure to ensure accurate measurements. Dark curtains, black matte surfaces, and floor coverings that have a textured surface work best for dampening the reflected light. If a screen is being used (i.e., front projector system), then the environment must also have dark walls, ceilings, and floors to prevent stray light from reflecting off these surfaces onto the screen. This is particularly important during the illuminance calibration process. Dark curtains and floor coverings that have a textured surface work best for dampening the reflected light. In addition, some mechanism for positioning the display at the appropriate working distance from the imaging colorimeter must be implemented. This can either be done manually or with a mechanical system.

Implementation of JND for Automated Display Testing

Once an image of the display is captured, the JND analysis function processes the image to generate a JND map. The algorithm also outputs three JND metrics that may be used to grade the visual quality of the display. This has immediate value for production-line applications; for example, in both display fabrication facilities and final assembly lines. The generated metrics are:

(1) Aperture: The aperture function represents the fovea vision of the eye. Aperture is a localized metric that indicates the visibility of artifacts at each point in the image. The aperture JND metric at each display pixel reflects the visibility of artifacts in a region in the neighborhood of that pixel, when the observer is fixated on that pixel. The output of the Aperture metric is thus an image (JND image). The Aperture metric is best suited to small local artifacts, such as typical spot mura. The **Max JND** metric is the maximum value found in the JND image.

(2) Total JND: The result of a nonlinear pooling across the JND image. It gives an overall measure of the visibility of artifacts in the image. It is most useful when the image contains several artifacts at different locations in the image.

(3) Single JND: The result of a nonlinear pooling across the JND image. It gives an overall measure of the visibility of artifacts in the image. It is most useful when the image contains several artifacts at different locations in the image.

The JND analysis was implemented with a number of input options that are detailed in Table 1. The input options increase testing flexibility, allowing the JND analysis to be applied to a broad range of measurement situations.

Option or Parameter	Description
Down-Sample	<p>The image may be down-sampled to decrease the processing time.</p> <p>Down-sampling normally has small to negligible effects on the resulting JND values, unless the down-sampling is excessive. Typical values are 2x2.</p> <p>For example, 2x2 down-sampling will select every other row and column for processing. No averaging is done; the skipped rows and columns are simply ignored.</p>
Save to Database	<p>When <i>SaveToDatabase=True</i>, the resulting JND image will automatically be saved to the current measurement database at the conclusion of the processing. In addition, a difference image will also be saved showing the contrast <i>difference</i> between the test image and a calculated reference image.</p> <p>In every case, the final JND image can be manually saved to the database by executing separately the “SaveToDatabase” image process.</p>
Viewing Distance	<p>The viewing distance parameter is the approximate distance at which a human observer would evaluate the display. It is not the camera distance.</p> <p>The viewing distance value is specified in units of the display height. For example, a value of 2 indicates the viewing distance is equal to 2 times the height of display.</p> <p>Changing the viewing distance has the effect of making artifacts more or less visible. A small point defect may be visible at close viewing distance, but less visible or not visible when viewed farther away.</p>
Region of Interest	<p>A region-of-interest (ROI) inside the measurement may be defined for mura analysis by dragging a rectangular region with the left mouse button on the bitmap image. The region-of-interest will appear as a solid white rectangle. It is not necessary to crop the measurement to this region-of-interest. The image process will utilize the image area defined by the white rectangle.</p> <p>If no region-of-interest is supplied by the user, the image process will automatically find the active display area in the measurement image, removing the dark border surrounding the image, if there is one. If there is not a well-defined edge defining the active display area, then the user should provide a region-of-interest.</p>
TristimType	<p>If a single tristimulus image (<i>TrisX</i>, <i>TrisY</i>, or <i>TrisZ</i>) is selected in the parameter table, then the image process will operate only on that tristimulus image. The other two tristimulus images will be dropped.</p> <p>If the <i>TristimType</i> selected is <i>All</i>, the image process will be applied to all three tristimulus images in the case of a color measurement; or to the <i>TrisY</i> image in the case of a monochromatic image.</p>

Table 1. User-defined input options in TrueMURA Software JND analysis.

Measurement Examples

The JND analysis algorithm defined above has been applied to many different display image samples to test its usefulness. The technique has been demonstrated to work well in identifying mura; and most importantly the computed JND value provides a numerical assessment that can be used to grade different mura or displays.

Figures 4, 5, and 6 show the application of the algorithm to an LCD display. In this case a white test image is displayed on screen. Two JND maps of the display are shown: raw JND image, and a JND map with a false-color scale to provide a visual distinction

between areas of high and low luminance. In Figures 7 and 8, the JND algorithm is applied to an LCD projector screen image. In this case, very obvious mura at the center of the image is readily identified. The JND analysis can be applied to any other uniform screen image, including black screens.



Figure 4. LCD measurement with gradients near the edges of the display and two mura defects near the center. The mura at the center are barely noticeable in the original image.

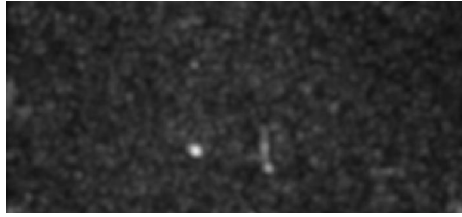


Figure 5. The raw JND analysis of the display image clearly shows the mura at the center of the screen. Some artifacts (light leakage and dark spots) at the edge of the display are also visible. This analysis highlights mura that were barely visible in the original image.

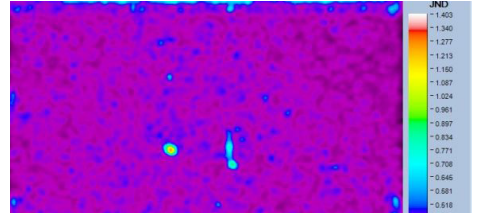


Figure 6. In this false-color representation of the JND map, it is clear that the two spots in the center of the display and some areas along the bottom of the display have JND values greater than 1 (the threshold value for being “just noticeable”). The speckled area across most of the display—apart from the mura at the center and along the edge—represents JND values of about 0.7 or lower and could be accepted or rejected based on pass/fail tolerance setting in the software.

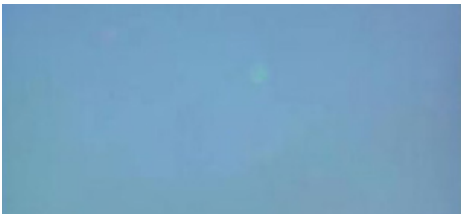


Figure 7. An image taken of a white display from an LCD projector—mura in the center of the screen image is readily visible.

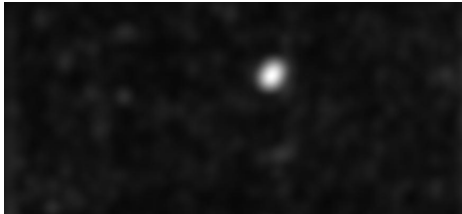


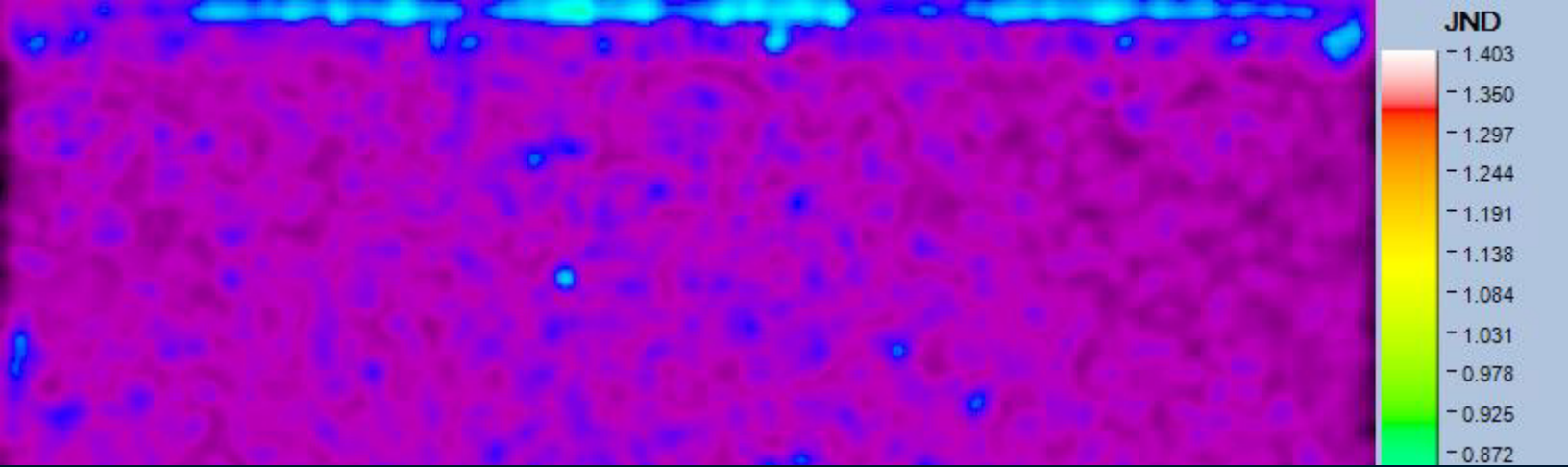
Figure 8. The JND image computed from the LCD projector measurement. The Max JND, Total JND, and Single JND values allow grading of various attributes of display performance.

Conclusion

Display defect detection performed using a colorimetric imaging system and SSO-based JND algorithms demonstrates that JND analysis is an effective means of obtaining additional information about display image quality that extends beyond both human inspection and traditional automated analyses. This analysis system can be applied to any display type, including LCD, LED, mini- or microLED, and OLED, enabling consistent and quantifiable evaluation of any display device according to human visual perception and quality control based on the consumer experience.

References

1. Watson, A.B., “The Standard Spatial Observer: A new tool for display metrology,” Information Display 23(1), (2007).
2. Rykowski, R. and Kostal, H., “Imaging Colorimetry: Accuracy in Display and Light Source Metrology,” Photonics Handbook (2008).



Correlating human perception of defects with data offers a unique opportunity to objectively detect and quantify display quality. By applying algorithms for JND image uniformity analysis, imaging colorimeters are able to perform efficient and repeatable automated inspections with equivalent optical sensitivity and tolerance for defects as compared with human inspectors.

GLOBAL OFFICE LOCATIONS

Radiant maintains direct sales, engineering, and support offices and personnel throughout North America, China, and Korea. Radiant is also sold and supported in other areas of the world by our sister offices in the Konica Minolta Sensing Business.

AMERICAS

Global HQ **Radiant Vision Systems**
 18640 NE 67th Ct.
 Redmond, WA 98052 USA
 +1 425 844-0152
Info@RadiantVS.com

Regional Offices Cupertino, California
 Novi, Michigan

ASIA

China HQ Shanghai, China
Regional Offices Shenzhen, China
 Suzhou, China

Japan Tokyo, Japan
Korea Seongnam, South Korea
Taiwan Zhubei, Taiwan
Asia-Pacific Singapore

EUROPE

Europe HQ Nieuwegein, Netherlands

Regional Offices Diegem, Belgium
 Paris, France
 Munich, Germany
 Milan, Italy
 Wrocław, Poland
 Vastra Frolunda, Sweden
 Dietikon, Switzerland
 Istanbul, Turkey
 Warrington, United Kingdom



A Konica Minolta Company

Contact your local Radiant office at www.RadiantVisionSystems.com.

Copyright ©2020 Radiant Vision Systems LLC. All rights reserved. Specifications are subject to change without notice. Radiant, Radiant Vision Systems, ProMetric, ProSource, VisionCAL, and Source Imaging Goniometer are registered trademarks of Radiant Vision Systems LLC. 2020/12/14