Instrument Systems
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Display Testing and Spectrometry with Multiple Colorimetric Observers

Display technologies such as OLED, QD-OLED, Mini-LED and MicroLED-based systems often rely on narrow-band emission spectra. When these displays are calibrated using only conventional CIE 1931 2° color-matching functions (CMFs), they may share the same measured white point while still appearing different to observers. This application note presents the use of multiple colorimetric observers for enhanced display testing.

LumiTop Imaging Workflow
The LumiTop workflow combines spatially resolved imaging with spectroradiometric measurements and supports color conversion using CIE 1931 2°, CIE 1964 10°, CIE 2015 2° and 10°, as well as customer-defined observers.

Spectrometry Workflow
SpecWin Pro and CAS.dll support the post-processing of measured spectra using different colorimetric observers. In addition to the standard CIE 1931 2° observer, users can select CIE 1964 10°, CIE 170-2:2015 2° and 10°, or custom observers to calculate tristimulus values and color coordinates.

The use cases described in this document cover metameric mismatch and user-specific evaluation in order to reduce observer metamerism failures for different display technologies and target groups. It also describes the use of application-specific observers for low-light conditions, automotive and aviation applications, as well as closed-loop process control in display production. This multiple observer approach enables a more comprehensive characterization of display appearance while preserving established standardized photometric quantities

APPLICATION
NOTE

\\ 1. INTRODUCTION

New display light-source technologies can cause a phenomenon known as metameric mismatch. This means that two displays can be calibrated to the same white point but still appear different to the same observer because they have different emission spectra. Figure 1 shows an OLED reference display (left), an LCD display (center), and a second OLED display (right) with a different spectrum. All displays are matched to the same white point (Fig. 3) in CIE 1931 color space. The different white spectra of these displays are depicted in Table 1.

To a typical observer, the center display may show a noticeable color shift, while the right-hand display may appear closer to the reference OLED. This effect is caused by the color-matching functions (CMFs) used to convert a light spectrum into a colorimetric value. The CIE 1931 CMFs are widely used and also provide the basis for calculating traditional photometric quantities such as luminance and color temperature. However, they have known limitations and can contribute to color differences when displays with different spectra are matched.

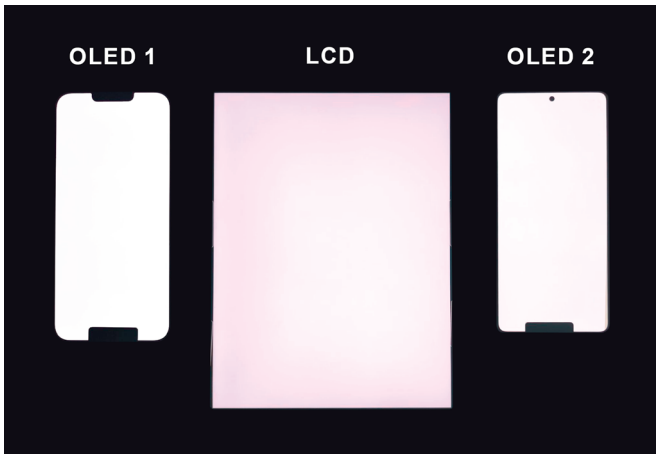


Fig. 1: Three displays with different emission spectra — a reference OLED display (left), an LCD display (center), and a second OLED display (right). Although the displays are matched to the same white point using the CIE 1931 2° observer, they may appear differently colored because of metameric mismatch.

White-light emission spectra

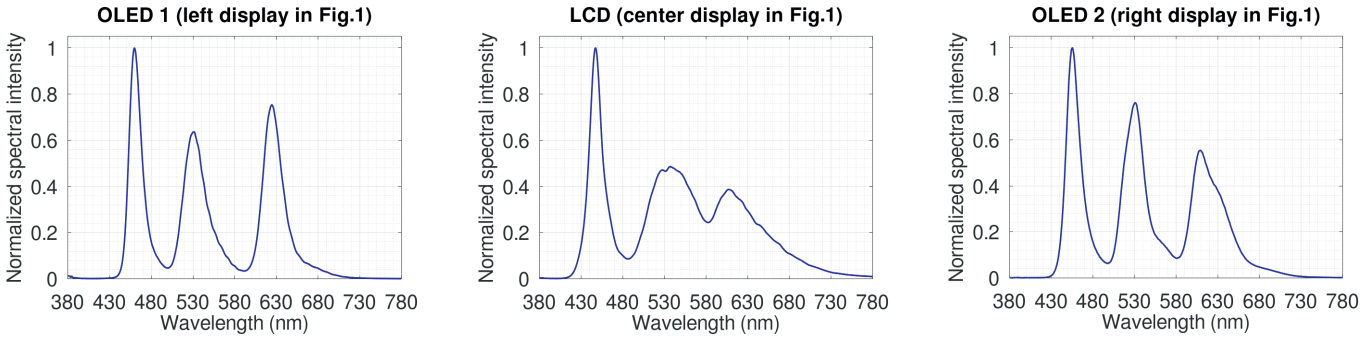


Table 1: Comparison of the white-light emission spectra of the displays shown in Figure 1.

The CMF plots in Figure 2 show clear differences between the observer models. In the blue spectral region, around 445 nm, the CIE 1931 2° function has a lower value than the corresponding functions of the newer observers. This means that the same amount of blue light contributes less to the calculated color value when the CIE 1931 observer is used. As a result, a display matched with the CIE 1931 observer may contain more blue radiant power while still reaching the same target white point.

A similar difference can be seen in the red spectral region, around 600 nm. Here, the CIE 1931 functions also assign a different, generally lower contribution to the red part of the spectrum than the newer observer models. Therefore, displays matched to the same white point can have different amounts of blue and red light depending on which observer model is used. The exact difference depends on the complete emission spectra and on the matching procedure.

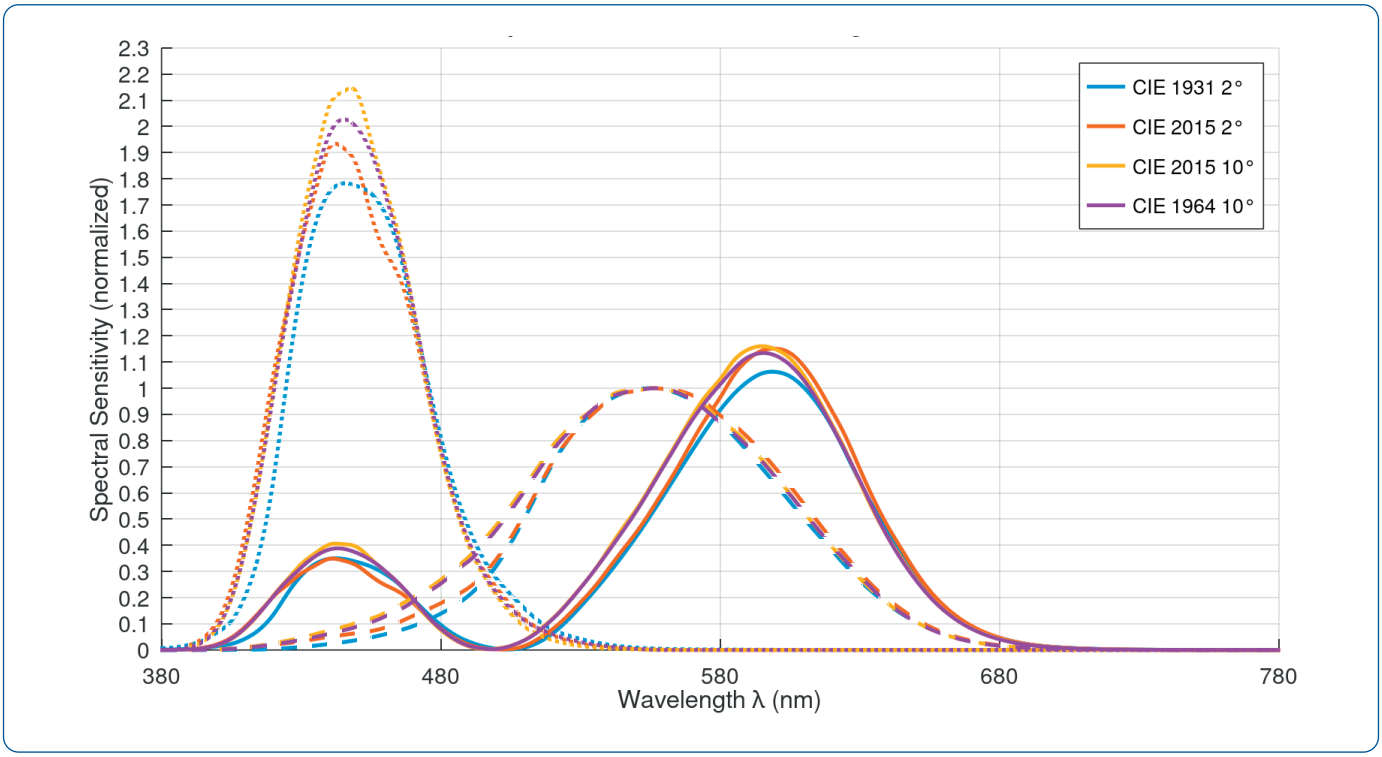


Fig. 2: Comparison of the CIE 1931 2°, CIE 1964 10°, and CIE 2015 color-matching functions with the spectral sensitivities of the tristimulus values X (solid line), Y (dashed line) and Z (dotted line).

Figure 3 shows the transformation of the display chromaticity coordinates from the CIE 1931 2° to the CIE 2015 10° color space. The left plot depicts the color space of the CIE 1931 2° observer. In this color space, the displays in Figure 1 were adjusted to a common white point. The chromaticity coordinates of the individual displays are close to one another in the CIE 1931 color space and would therefore appear nearly identical to an observer represented by the CIE 1931 2° CMF.

However, when the white spectra of the displays are transferred to the CIE 2015 10° color space (Figure 3, right), the chromaticity coordinates spread across a much wider color range. This is precisely the effect observed in the photographs in Figure 1. To an observer represented by the CIE 2015 10° CMFs, the displays appear differently colored.

The CIE 2015 observer is currently regarded as one of the most representative standardized observer models. Compared with the CIE 1931 observer, it provides a more accurate description of human color perception, particularly in the red and blue regions of the visible spectrum.

To reduce this mismatch problem, it can be useful to perform color matching with an alternative CMF. At the same time, customers might want to preserve their results in the CIE 1931 color space, for their established connection to conventional colorimetry and photometry. LumiTop instruments provide a simple way to apply this approach. The workflow is described in the next section.

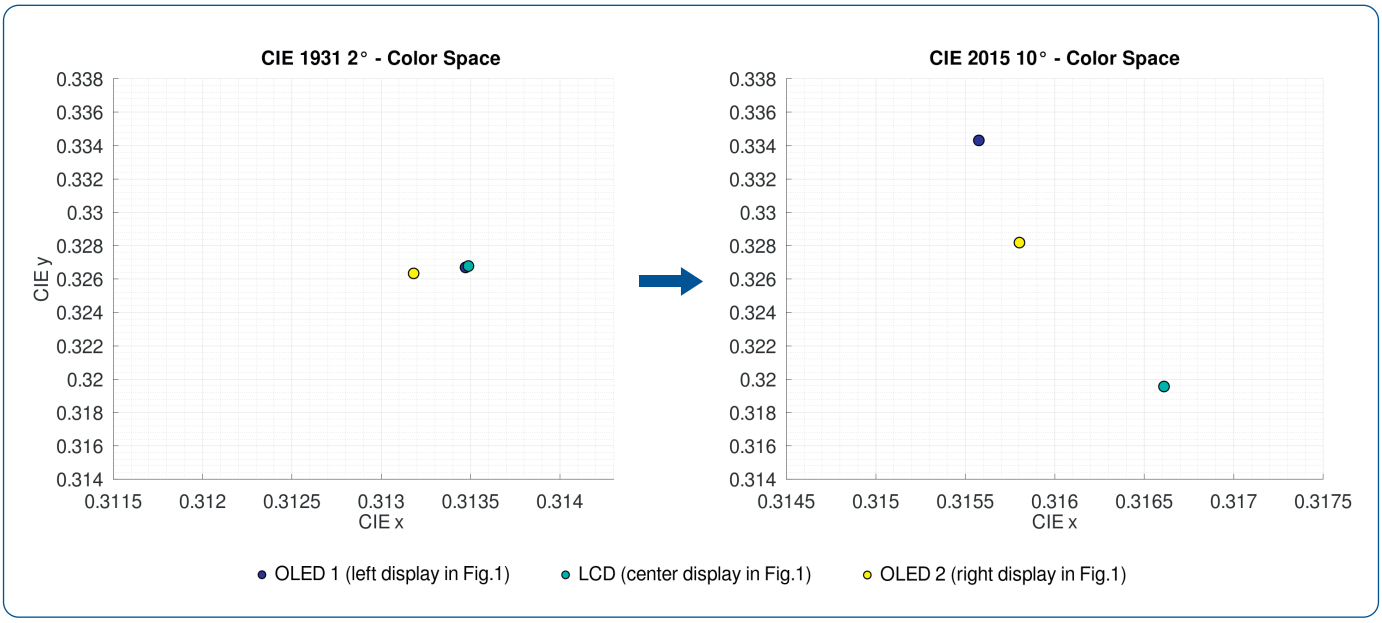


Fig. 3: Transformation of the display chromaticity coordinates from the CIE 1931 2° to the CIE 2015 10° color space. Although the displays are matched to a common white point using the CIE 1931 2° observer, their chromaticity coordinates spread over a wider range when evaluated with the CIE 2015 10° observer.

\\ 2. CUSTOM CMFS AND WORKFLOWS

2.1. LumiTop Imaging Workflow

LumiTop imaging colorimeters developed by Instrument Systems provide a new feature extending the colorimetric measurements to a wide variety of colorimetric observers, including: CIE 1931 2°, CIE 1964 10°, CIE 2015 2° and 10° as well as customer-defined observers. A workflow for enhanced display measurement with variant observers is shown in Figure 4.

The processing workflow has the following steps:

» Step 1
Hybrid acquisition of the 2D RGB image and the spectrum of the DUT.

» Step 2a
The MyCal functionality is required: A user-selected CMF can be chosen for the color conversion to CIE XYZ tristimulus values. Options are CIE 1931 2°, CIE 1964 10°, CIE 2015 2° and CIE 2015 10°, or customer-defined observers. The color-conversion matrix is generated using the CMFs of the selected observer, and converts the RGB image into the corresponding CIE XYZ tristimulus values.

» Step 2b
Color tristimulus values for the selected observer are calculated from the spectral spot measurement.

» Step 3
The CAS tristimulus values are used to fine-correct the 2D XYZ image. Thus, the final result is a spectrally corrected, high-resolution hybrid image that combines the CAS 140D's absolute accuracy with the LumiTop's imaging speed and spatial detail.

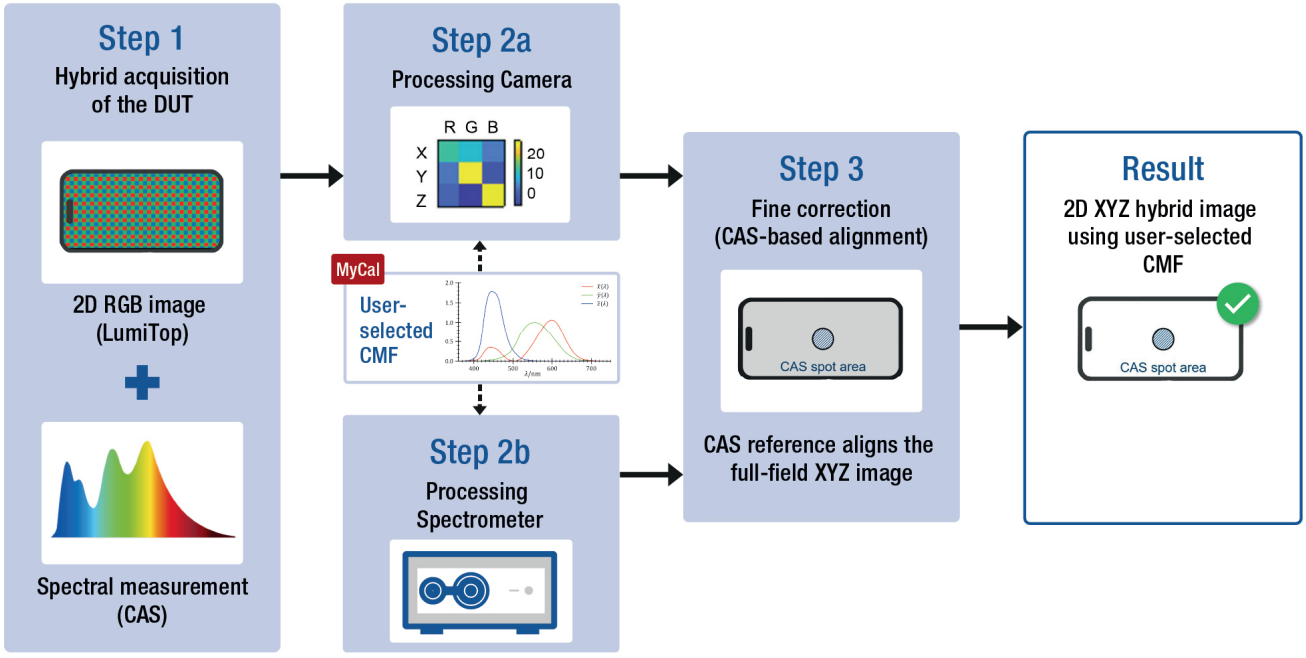


Fig. 4: Custom CMF processing workflow of the LumiTop.

2.2 CMF Post-Processing in SpecWin Pro and CAS.dll

For spectrometry applications, the SpecWin Pro and CAS.dll offer the possibility to post-process spectra measured with the standard observer using both pre-defined other standard observers or custom observers.

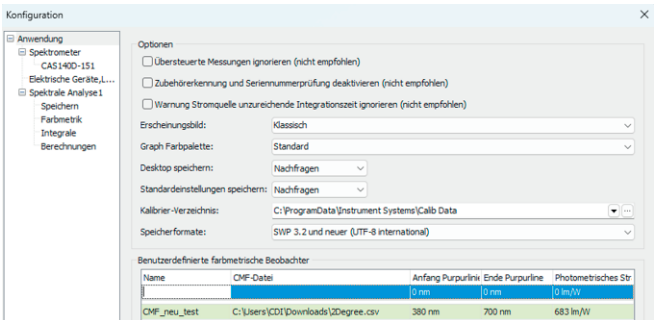
» Step 1

Measure the DUT. By default, the results are calculated using the CIE 1931 2° standard observer.

» Step 2

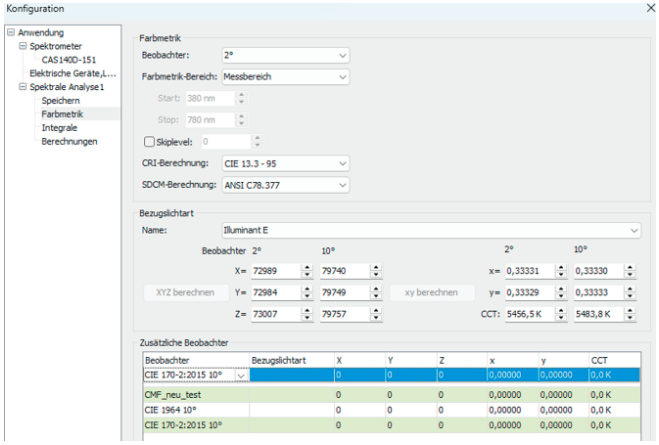
To use a custom observer, import your color-matching functions into the user-defined CMF list. Enter the photometric equivalent K_m and the start and end points of the purple line.

Note that these points do not necessarily correspond to the lowest and highest wavelengths in the CMF data.



» Step 3

Select the predefined or custom observers to be used for the colorimetric calculations in the colorimetric settings.



» Step 4

Compare the calculated tristimulus values and color coordinates for the selected observers in the Inspector dock window.

Zusätzlicher Beobachter 4	CIE 170-2:2015 10°
Bezugslichtart	(0,0000;0,0000)
Tristimulus_X	26,21 cd
Tristimulus_Y	25,58 cd
Tristimulus_Z	27,34 cd
Farbkoordinaten	
x	0,33127
y	0,32322
z	0,34551
u	0,21317
v 1960	0,31198
v 1976	0,46798
Dominante Wellenlänge	-1,00 nm
Farbsättigung	1,000
CCT	5549 K
Planck Abstand	-8,7E-003
Zusätzlicher Beobachter 5	CIE 1964 10°

\\ 3. USE CASES

3.1 Application of customized CMFs while preserving photometric traceability

In the CIE 1931 colorimetric system, the $\bar{y}(\lambda)$ CMF closely approximates the normalized photopic luminous-efficiency function V(λ). As a result, the conventional Y tristimulus value is closely related to photometric luminance. The $\bar{y}_{2015}(\lambda)$ function of the CIE 2015 observer, however, has a different spectral sensitivity and is not identical to the function used for photometric measurements.

This distinction is particularly important for colorimeters, in which the CMFs are approximated in hardware by a specific combination of filters and detectors. If a colorimeter is equipped with filter characteristics adapted to the CIE 2015 CMFs, its Y signal is no longer directly traceable to conventional photometric luminance and must not be interpreted as a photometric luminance value without further qualification.

This distinction is especially relevant for spectrally narrow-band light sources. Under these conditions, the calculated CIE 2015 tristimulus values and the photometric luminance can differ significantly.
For this reason, users want to maintain the tristimulus values according to CIE 1931 in order to keep their photometric reference.

Against this background, LumiTop devices offer a clear advantage over filter-wheel-based colorimeters, as their spectroradiometer-based measurement principle enables flexible, software-defined evaluation according to different observer functions while preserving traceability to the conventional photometric reference, without requiring any hardware modifications.

In addition to display calibration, custom CMFs can be used during product development to identify critical emission spectra at an early stage and to select more suitable primary colors. Evaluating the same spectrum with multiple observer models can reveal whether certain observers may perceive a color shift. This creates the basis for a more comprehensive colorimetric description of display appearance.

In this context, it is worth noting that certain consumer electronics manufacturers, including Apple [1] and Xiaomi [2], are reported to use custom CMFs for the development and evaluation of their display products.

3.2 User-specific CMFs for different target groups

A recent study shows significant interindividual variability in the spectral sensitivities of the rods and cones in the human eye [3]. As a result, different people may perceive the same colors differently. This does not indicate a color vision deficiency, but rather reflects natural individual variation among healthy observers.
Custom CMFs can be used to reduce matching errors between different observers or to adapt a device to specific target groups—for example, by taking age-related changes in lens density into account.

The following figure shows the variation in cone sensitivity curves for 100 observers between 8 and 80 years of age, based on a 2° field of view. Against this background, it may be beneficial to evaluate displays for different user groups using appropriately adapted CMFs.

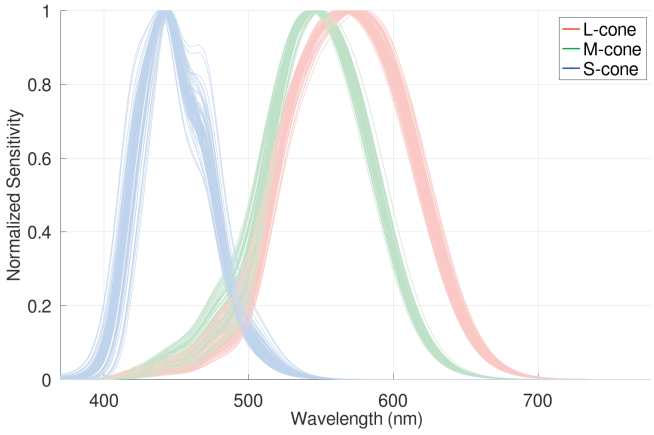


Fig. 5: Individualized color-matching functions for 100 observers aged 8 to 80 years [3], illustrating the interindividual variation in cone spectral sensitivities for a 2° field of view.

3.3 Task-specific CMFs for low-light or automotive applications

In addition to individual differences between observers, the viewing context can also justify the use of different CMFs or observer functions. The appropriate functions may depend on the size of the field of view and the observer's adaptation state. For example, different functions are used to describe:

- Different visual field sizes
- Different levels of visual adaptation:
  1. Photopic vision: V(λ)
  2. Mesopic vision: V_{mes} (λ)
  3. Scotopic vision: V' (λ)

Photopic evaluation based on V(λ) remains the standard approach for display luminance measurements. Scotopic and mesopic luminous efficiency functions are mainly relevant for displays intended for low-light or night-time applications, such as automotive instrument clusters, aviation displays and night-vision systems. In these cases, the spectral composition of the display can influence perceived brightness differently from the conventional photometric luminance.

Automotive displays are a representative example of an application in which viewing conditions can vary considerably. They are observed during both daytime and nighttime, under changing ambient brightness, at different viewing distances and across relatively large fields of view.

In such cases, adaptation-specific or task-specific custom CMFs can provide a more suitable basis for display evaluation.

However, it is important to distinguish these functions from CMFs in the strict colorimetric sense. The scotopic function primarily describes spectral luminous sensitivity under scotopic conditions and is not an alternative CMF in the same sense as the CIE 1931 or CIE 2015 CMFs.

This example nevertheless illustrates the flexibility and broad applicability of the Custom CMF feature in industry. It allows the observer model used for evaluation to be adapted not only to individual differences between observers, but also to the specific viewing conditions, application and task.

3.4 CMF-based process control for display production

Different CMFs can provide significant added value in display production even before post-measurement analysis.

In spectral measurements the CMF can be changed flexibly and the resulting data can trigger a specific process action without delay. For each tested panel, the following parameters can be determined, for example:

- the white point,
- the deviation according to CIE 1931,
- the deviation according to CIE 2015,
- the variation of the results across multiple observer models.

Combining several observer models can help to assess not only a panel's deviation from a single standard, but also its robustness under different viewing conditions.

If this information is transferred directly to the test and control software, the measurement station can correct the display settings, calculate a suitable calibration matrix, assign the panel to a defined bin, reject faulty units or adaptively select the next measurement.

If CMF evaluation is performed only as a subsequent post-processing step, it remains limited to a documentation or diagnostic function. Direct intervention in the ongoing production process is then no longer possible. In this application context, CMFs are therefore not used solely as analytical evaluation models, but as directly effective control parameters within a closed-loop testing and production process.

\\ 4. CONCLUSION

The use of multiple colorimetric observers extends display testing beyond a single standardized representation of color appearance. While the CIE 1931 observer remains essential for established photometric relationships and comparability, alternative and customer-defined color-matching functions can reveal observer-dependent differences that are particularly relevant for displays with narrow-band spectra.

The four use cases demonstrate how multiple CMFs can extend display evaluation: preserving photometric traceability while applying customized CMFs; accounting for observer-specific characteristics and target-group requirements; adapting evaluation to low-light, automotive and other task-specific viewing conditions; and integrating CMF-based results into production decisions such as calibration, panel binning, rejection and adaptive measurement. In this way, CMFs become an actionable production criterion rather than merely a post-measurement research parameter.

Custom CMFs should therefore not be regarded as a replacement for standardized observers, but as a complementary tool for application-specific analysis and decision-making. Instrument Systems CAS spectroradiometers [4] and LumiTop imaging colorimeters [5] fulfill this requirement by enabling data analysis with multiple observers in parallel or post-measurement.

\\ REFERENCES

[1] *Stockman, Andrew, Rider Andy, Imai, Francisco, et al. (2026), Display Color Consistency, Display Week, May 3rd 2026, Los Angeles.*

[2] *Xiaomi (2026): Xiaomi 17. Product advertisement. Available online at: https://www.mi.com/de/product/xiaomi-17 (accessed 21 September 2026).*

[3] *Keyu Shi, Ming Ronnier Luo, Andrew T Rider, Siyuan Song, Tingwei Huang, and Andrew Stockman, „Individual color matches and cone spectral sensitivities in 100 observers of varying age,“ Opt. Express 32, 48051-48071 (2024)*

[4] *Instrument Systems GmbH (2026): Spectrometers. Available online at: https://www.instrumentsystems.com/en/products/spectrometers (accessed 21 September 2026)*

[5] *Instrument Systems GmbH (2026): Imaging Colorimeters and IR Testing Cameras. Available online at: https://www.instrumentsystems.com/en/products/imaging-colorimeters-ir-testing-cameras (accessed 21 September 2026).*

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