Forward and inverse colour calibration models for OLED displays

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Introduction

OLED displays can achieve high luminances along with larger colour gamuts. Many OLED display manufacturers use an additional white primary to supplement the red, green, and blue channel responses which makes the transformation between the display native RGB and device-independent colorimetric values (e.g. XYZ) non-linear.

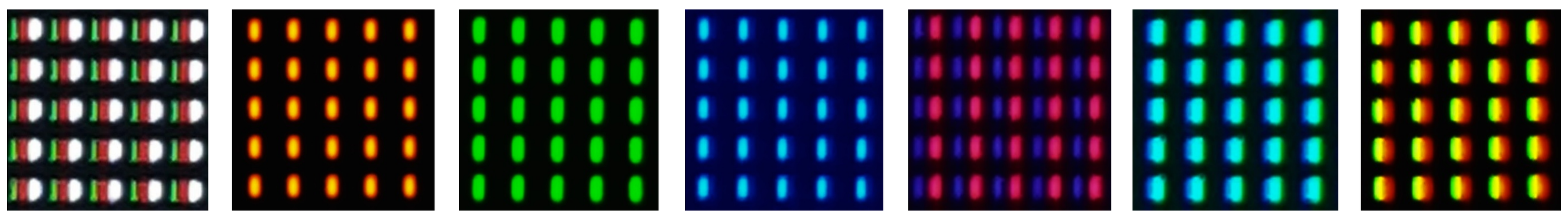

Figure 1: Sub-pixel images for white, red, green, blue, magenta, cyan, and yellow colours on LG G2 OLED

- Assessment of OLED color models in the literature focused on forward display accuracy[1,2,3]. Forward models convert encoded pixel values (e.g., sRGB, BT.2100) to emitted light colorimetric values (XYZ, linear BT.2020 RGB)
- Inverse models are crucial for practical use: they map desired colorimetric values to display-encoded pixel values
- OLED display models are non-bijective, complicating direct inversion. Potential for lower performance in inverse models relative to forward models due to non-invertibility issues.

Display Measurements

Measurement Setup:
- Evaluated two 55-inch OLED TVs: LG OLED Evo G1 and G2
- Used Psychtoolbox[4] with MATLAB on Windows 10, HDR enabled
- Consistent settings on both TVs for unbiased comparison
- Measurements conducted in a dark room with native gamut and all enhancements off

Data Collection:
- Three measurement sets (RGBXYZ) collected: ramps, grid, and test
- Used Konica Minolta CS-200 colorimeter
- Measurements taken from screen center, with test patches covering 5% of screen

Measurement Types:
- Ramps: The individual responses of each of the R, G, B, and W channels were measured using 120x4 HDR10 pixel values and used to estimate the EOTF of the displays.
- Grid: 13x13x13 RGB grid of HDR10 values to refine transformation matrices and compute 3D LUTs
- Test: Evaluated model performance with ColorChecker colors under Illuminant C at varying luminance (1 to 500 cd/m²)

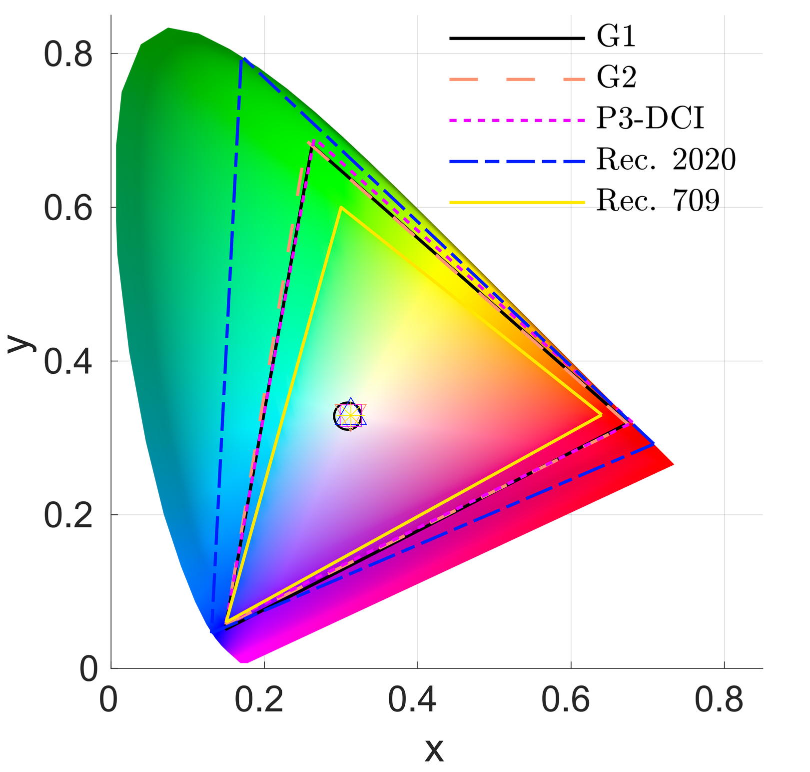

Figure 2: Gamut of our OLED displays compared with Rec. 2020, Rec.709, and P3-D65 color spaces. The lines show the RGB primaries, and the markers show the un-calibrated white points of the displays and those of the standard color spaces.

Figure 3: Colours of the X-Rite ColorChecker taken under Illuminant C and scaled them to five different luminance levels: 1, 4.7, 22, 106 and 500 cd/m2 to generate a set of 120 colour coordinates and measured the display responses

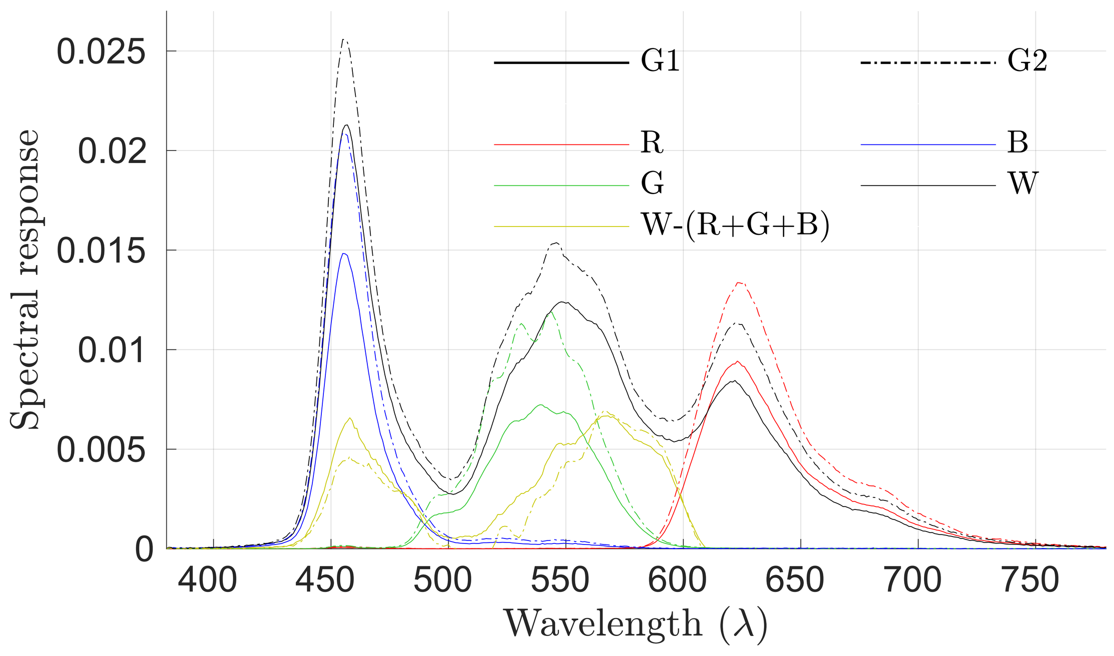

Figure 4: Emission spectra of the displays. The white sub-pixel responses (black lines) are not equal to the sum of the red, green, and blue responses demonstrating the non-additivity in the color response of the display

Modelling

Three sub-gamut[3]:
- Divides RGBW gamut into three sub-gamuts (RGW, RBW, GBW)
- Uses transformation matrices for each sub-gamut
- Extended with a 3D LUT for residual error correction

PLCC-based compensation[2]:
- Employs PLCC (Piece-wise Linear interpolation assuming Constant Chromaticity) method for intermediate XYZ value prediction
- Applies a 3D LUT to address prediction errors

Colur Mixing[1]:
- Utilizes two transformation matrices: one for high chroma (M_{rgb}) and one for low chroma (M_{gray})
- Final XYZ values obtained from a weighted sum of both matrices

Polynomial Regression[1]:
- 3rd order polynomial regression with a 14x3 matrix
- Polynomial terms include linear, square, and cubic RGB terms and their interactions

RGBW Gamut:
- Assumes independent linear combinations of RGBW primaries
- Tests the simple model against more complex methods

Validation

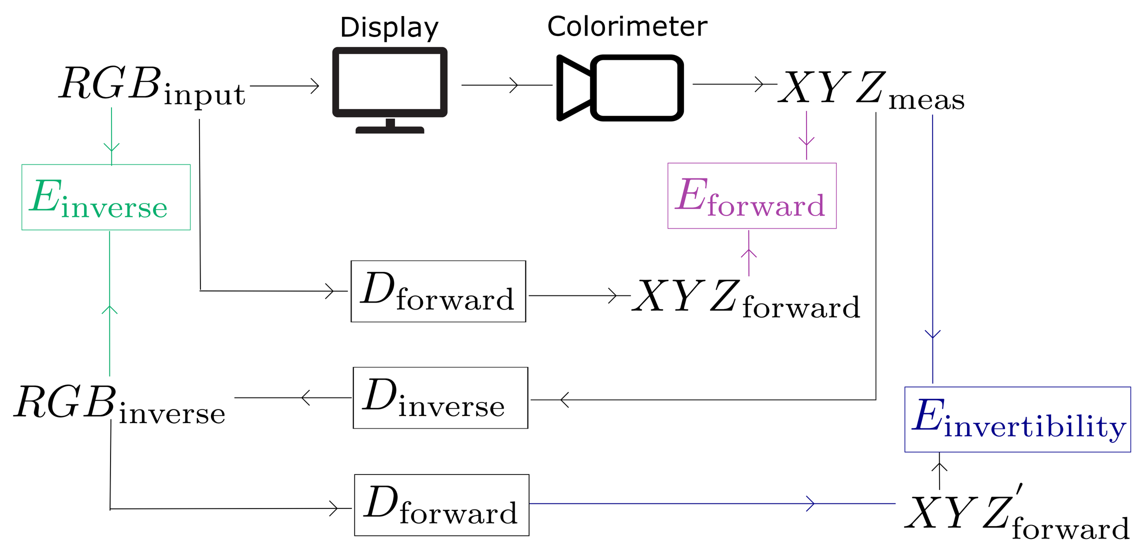

Figure 5: Model validation flowchart. $D_{forward}$ represents the forward models and $D_{inverse}$ represents the inverse models. $E_{forward}$ is the forward model error, $E_{inverse}$ the reverse model error, and $E_{invertibility}$ is the invertibility test error.

- Forward Model Error

$$E_{forward} = \Delta E_{00}(D_{forward}(RGB_{input}), XYZ_{meas})$$

- Inverse Model Error

$$E_{inverse} = \left\| PQ\left(D_{inverse}(XYZ_{meas})\right) - PQ(RGB_{input}) \right\|_2$$

- Invertibility Test Error

$$E_{invertibility} = \Delta E_{00}(D_{forward}(D_{inverse}(XYZ_{meas})), XYZ_{meas})$$

Results

- **Forward Model**: 3-gamut and PLCC-based models had the lowest CIE ΔE00 for both G1 and G2 displays. PLCC-based model demonstrated slightly better performance on G2, likely due to differences in EOTF curves between the displays.
- **Inverse Model**: Colour Mixing model excelled in inverse error for G1. Both Colour Mixing and 3-gamut models showed strong performance for G2. Notably high maximum errors observed across all models for inverse errors.
- **Invertibility Test**: Invertibility performance varied significantly between the two displays. Best models for G1 invertibility were least effective for G2 and vice versa. Polynomial and RGBW-gamut methods displayed high invertibility for G1 but not for G2, hinting at a more non-linear utilization of the white primary in G2.

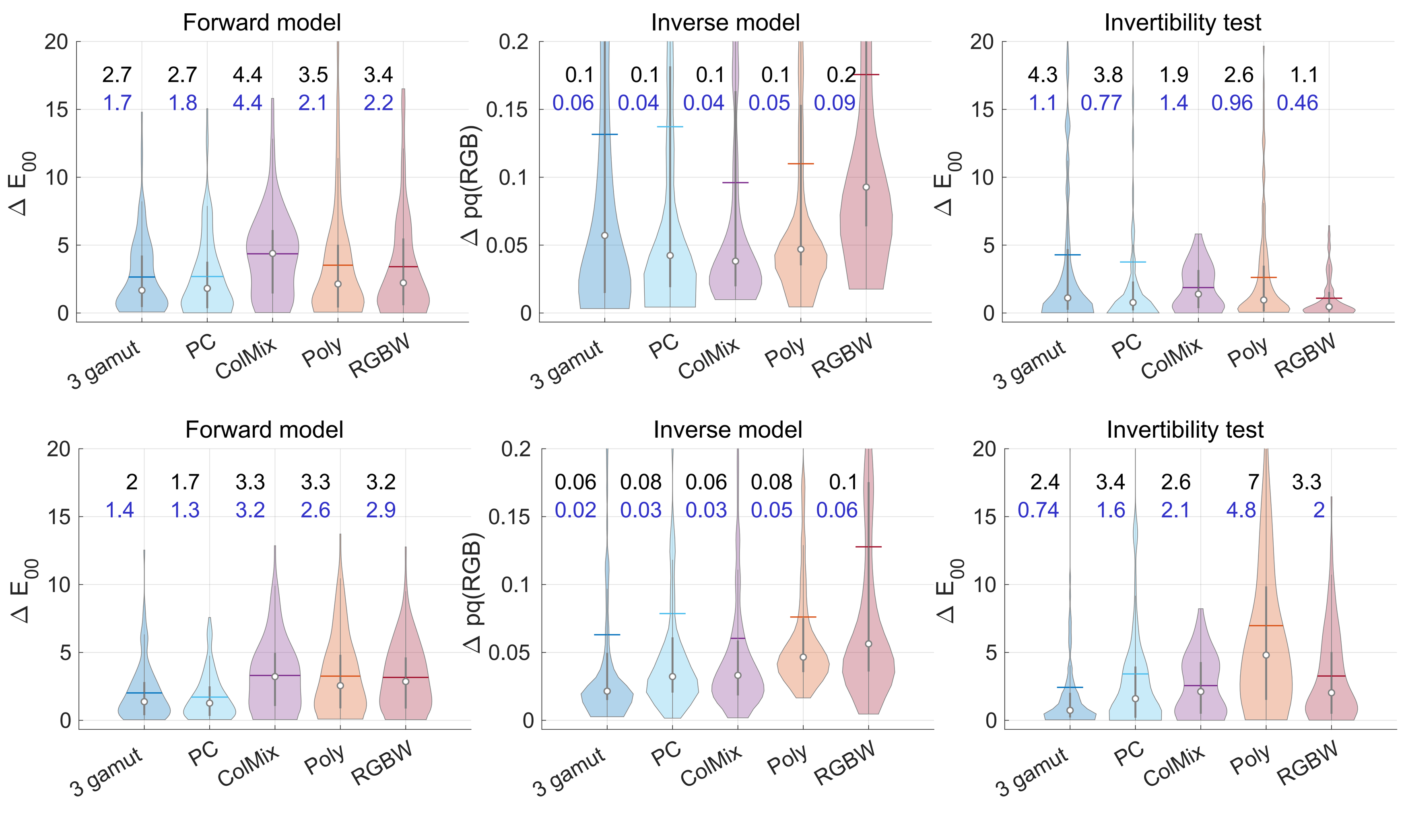

Figure 6: The distribution of errors for the G1 (top) and G2 display (bottom). The models are: 3-gamut, PLCC-based compensation (PC), Colour mixing (ColMix), Polynomial regression (Poly) and RGBW gamut. The white circle in each violin plots are the medians and the horizontal dash are the means. The black text at the top left of each violin is the mean, the blue text are the medians.

[1] P.-L. Sun and R. M. Luo, "Color Characterization Models for OLED Displays," SID Symposium Digest of Technical Papers, vol. 44, no. 1, pp. 1453–1456, 2013.
[2] D. Tian, L. Xu, and M. R. Luo, "The Characterization of HDR OLED Display," Electronic Imaging, vol. 31, pp. 326–1–326–6, Jan. 2019.
[3] B. Bodner and N. Robinson, "83-3: Calibration of Colorimeters for RGBW Displays," SID Symposium Digest of Technical Papers, vol. 50, no. 1, pp. 1206–1209, 2019.
[4] M. Kleiner, D. Brainard, and D. Pelli, "What's new in psychtoolbox-3?," 2007.