A comparison of LED panels for use in Virtual Production: Findings and recommendations

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Abstract

We evaluate four LED panels from three vendors for use in Virtual Production using experimental conditions. Tests were designed to assess Moire and scan-line artefacts, light reflectivity and grazing angle. We discuss LED manufacturing processes and the implications of these on visual artefacts, power consumption and colour fidelity, and conclude with results and recommendations for LED vendors, practitioners and procurement teams in Virtual Production.

1 Introduction

Virtual Production defines a set of production practices where practitioners work in and interact with virtual environments and technologies [8]. It reduces the need to move crews and equipment to location and enables remote working in (Virtual Reality, dramatically reducing CVD-19 risks, the environmental footprint, production costs and upends the traditional production process. The global VP market size is expected to reach £2.2b by 2026, rising at a rate of 14.3% per year [5]. It has been described [2] as "one of the greatest technical advances of recent years and holds the key to improving sustainability in the creative industries."

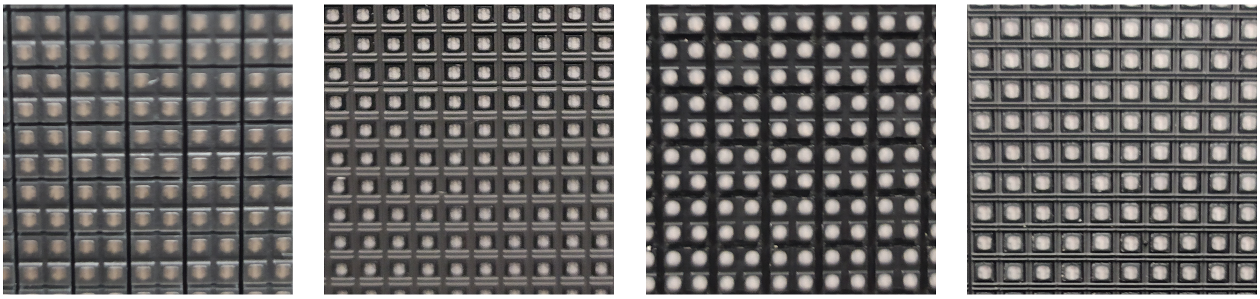
Panel	**Ruby 2.3**	**Black Onyx 2**	**RM2.3**	**PL2.5**
Vendor	ROE	ROE	AOTO	Absen
Pitch (mm)	2.3	2.84	2.3	2.5
Configuration	4-in-1 (common cathode)	SMD (common anode)	4-in-1 (common anode)	IMD SMD 4-in-1 (common cathode)
Scan Rate	1/8	1/11	1/6	1/8
Max Brightness (nits)	1500	1800	1800	1500
Resolution (pixels)	216x216	176x176	216x216	200x200
Weight (kg)	8.16	9.4	8.4	8.6
Power Consumption W/m^2 (Max/Average)	720/360	640/320	640/210	656/220
Viewing Angle (V/H)	140°/ 140°	140°/ 140°	160° ± 10°/ 160° ± 10°	160°/ 140°
Refresh Rate	3840 Hz	1920 Hz	7980 Hz	7680 Hz

Table 1: Comparison of selected panel specifications as provided by the vendors. In all cases this is for a single 500mm^2 panel.

While Virtual Reality, real-time rendering and motion capture technologies have been used previously on productions such as Lion King [17], it was not until The Mandalorian [6] that the loop between the real and the virtual was effectively "closed" by installing a LED wall on set. A photo–real virtual environment is rendered in real–time on a curved LED wall from the perspective of the camera. Performers that are filmed in front of the wall are illuminated implicitly by it, significantly reducing post–production costs — at least half of the shots on the Mandalorian where considered ”final pixel” quality, requiring no significant post–production [8].

The LED panels used in production were originally designed to be viewed by the human eye, not a camera sensor, leading to multiple challenges which affect filming practices on the virtual production set (see Section 2). As LED panel vendors adapt to this emerging market, it is becoming more important to design benchmarking practices to independently evaluate suitability of panels for use in Virtual Production.

This paper documents the experimental configuration and findings of a series of tests undertaken at Bournemouth University from 25 October to 3 November 2021. Four 1m^2 panels from three different vendors were installed for this purpose. We conclude with observations relating to the manufacturing process and how this may influence procurement decisions. The four panels tested were the ROE Ruby 2.3, ROE Black Onyx 2, AOTO RM2.3 and the Absen PL2.5.

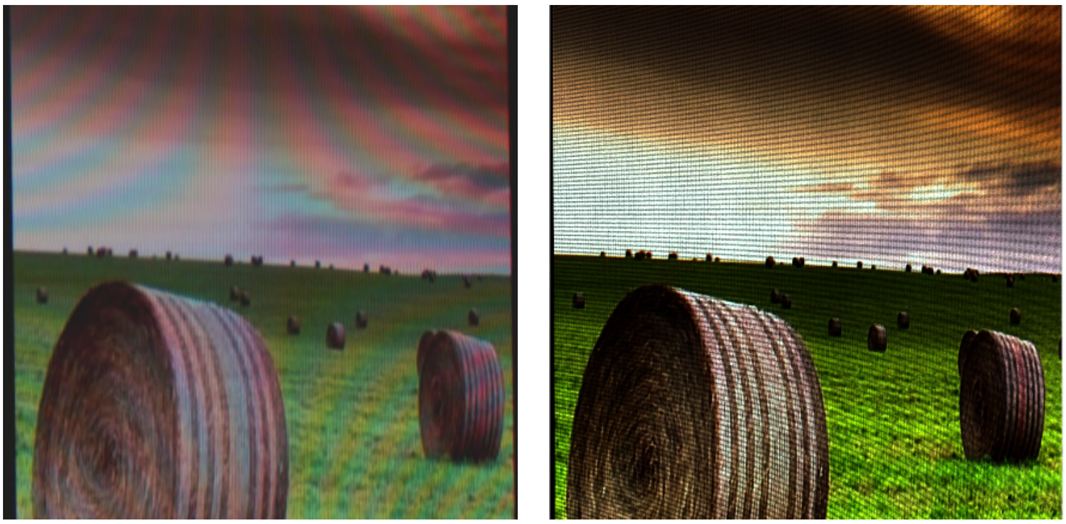


ROE Ruby 2.3 | ROE Black Onyx 2 | AOTO RM2.3 | Absen PL2.5

Figure 1: LED Pixel layout on the different panels. The topology of these LED layouts greatly influences the contrast ratio a panel can achieve. Images not to scale.

2 Experimental Design

The problems that arise when using LED walls in Virtual Production are well understood and are described in various sources including Kadner [8]:



(a) (b)

Figure 2: Moire artefacts can be reproduced using standard production software. A filmed image (a) is compared with a synthetic LED panel geometry, created in SideFX Houdini and rendered using Mantra, a Physically Based Renderer (b). While the artefacts cannot be exactly reproduced, it is possible to evaluate experimentally when they would be likely to arise. Full footage from (a) can be viewed here: https://youtu.be/vhF_nwIvEMs.

1. **Moire artefacts**: LED panels were designed for the human eye for outdoor and indoor displays. Using a camera sensor (laid out in a grid) to film an LED wall (also laid out in a grid) leads to predictable artefacts in footage that form in distracting, curved lines in the footage. These are easily detectable when filming close to the screen when it is nearly or entirely in focus (see, for example, Figure 2).

2. **Scanline artefacts**: While an LED wall refresh rate is typically very high, the LED wall refreshes in scan lines of a number of pixels determined by the density of the driver chips. A typical scan rate is 1/8, meaning that there is a driver chip for each of 8 pixels on the LED wall. If the camera shutter speed is not synchronised with the display, or moving quickly while filming the wall, the resulting image may have noticeable banding artefacts.

3. **Light reflectivity**: LED panels are excellent for providing soft environmental lighting in Virtual Production, but ineffective at providing hard / spot lighting. A common problem arises when the wall appears washed out due to the interaction between studio lighting and the LED panels.

4. **Reverberation**: Enclosing performers in a circle of flat LED panels results in significant audio reverberation. This can be mitigated to an extent through facility design, but LED panels do not currently factor in reverberation reduction as a design constraint to our knowledge. We were unfortunately not able to conduct experiments on audio reverberation during this test due to the small screen samples used.

5. **Grazing angle**: When filming LED panels the best performance is achieved when positioning the camera perpendicular to the screen. Colour reproduction deteriorates as the camera is rotated to be aligned with the wall. LED panels provide viewing angle measurements to support planning (see Table 1).

6. **Power consumption**: Sustainability is emerging as a key advantage of Virtual Production, with significant reductions reported in travel and transportation. External pressures to further reduce the carbon footprint are inevitable. Measured, rather than advertised, power draw under a typical experimental use case for Virtual Production to benchmark this property would have been a useful inclusion, but unfortunately these were not included in our experiments. We do however discuss these implications in Section 3.

(a) (b)

Figure 3: The studio configuration for the wall experiments. In (a) and (b) The full setup is visible, including the workstation, colour correct station, Brompton controllers, panels and camera, which is cabled to the Blackburst emitter. An inclinometer was used to ensure camera orientation was correct (b).

Unless otherwise stated, all tests were performed with the following default configuration:

- A Panasonic Varicam LT camera shooting in raw UHD (4k). Camera white balance is set to 3200K and shot in Rec 709.

- All footage has the Panasonic *Nicest Rec 709* Cube LUT applied.

- The four panels were driven by Brompton SX40 (ROE and AOTO units) or Brompton S8 (Absen unit only) processors.
- All of the above Genlock'ed using a Black Burst emitter.
- A graphics workstation (with NVidia A6000 RTX GPU) outputting a 12 bit HDR to both processors via HDMI.

Images from the general experimental setup are shown in Figure 3. All images used during the tests are shown in Figure 4.

2.1 Orthogonal track test

The orthogonal track test was designed to evaluate the presence of Moire and scanline artefacts with a dynamic camera in similar use scenarios to those used in Virtual Production. For the experimental configuration a set of square static HDR images were displayed (see Figure 4), rescaled to match the resolution of each panel.

(a) (b) (c) (d) (e)

Figure 4: Test images used in the experiment. Hay bales (a) and crypt (b) [21] are chosen to provide HDR reference for indoor and outdoor environments. The trees (c) [16] have geometric detail which could emphasise aliasing artefacts. Market (d) [13] is chosen to highlight contrast and colour reproduction. The Moon image (e) [14] demonstrates detail reproduction in very dark regions.

The camera is positioned on a Libec track ranging from 4.5m to 7.62m from the LED wall (note this is the range of the track, not the position of the sensor). The camera is capturing at 50Hz, 1/100 Shutter speed at ISO 100. A Zeiss Milvus 50mm lens was chosen to fit the LED panel in frame, and the aperture set to F4. The wall brightness was set to 1371 nits and white balance set to 3200K to match the camera.

For the experiment the focal point was set approximately 2 feet in front of the wall to simulate typical shooting scenario, so the wall starts on the track slightly out of focus. For the slow track, the camera is tracked at roughly 0.3 m/s away from the wall, and for the fast track the camera is tracked forward at 0.6 m/s towards the wall.

The results of this test can be viewed here: https://youtu.be/hreAZ0R_s9U. While the orthogonal track test was the most time–consuming of all the tests performed, the result was the least compelling. Under the rigorous experimental conditions scanline and Moire artefacts were barely noticeable, and we were unable to observe any differences between the panels. In comparison, in the mobile high frame–rate shoot (see Figure 2) these artefacts were very clearly observed.

2.2 Light reflectance test

Existing approaches to evaluating panel reflectance of external hard lighting are generally ad hoc, and might involve shining a torch at the screen. We designed an experiment to evaluate light bounce in a typical studio use case, evaluating each panel with as close to the same conditions as possible.

For this test we evaluated soft and hard light bounce off the LED panel. The LED panel was either completely off or displayed a green test pattern in the Rec 2020 achievable colour space. The camera sensor was positioned 2.83m orthogonal to each screen, and the same height as the centre of each screen (1.5m). Both the soft and hard (shown in Figure 5) were set up 4 meters from the screen, at 45° to the screen orthogonal. Note that this is similar to the tests performed by panel manufacturers to assess the contrast ratio, although was developed specifically to assess reluctance in typical Virtual Production applications.

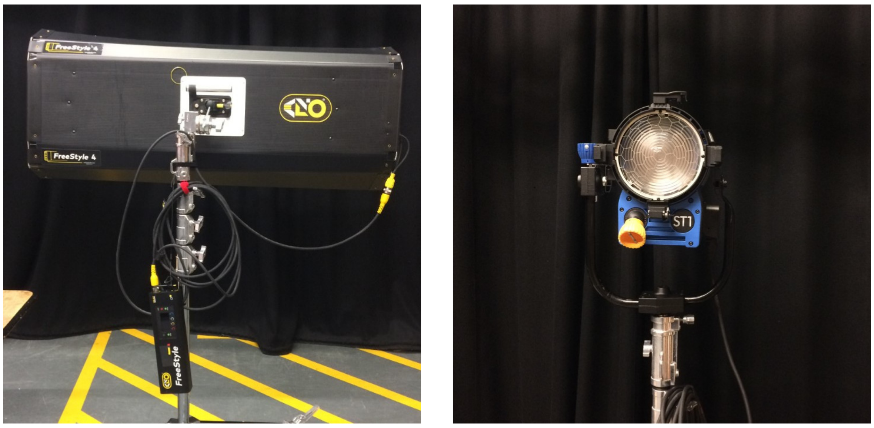


Figure 5: Left to right: the Kino Flo Freestyle 4 soft light and Arri ST1 spot light used in the Light bounce test.

The soft light used was the Kino Flo Freestyle 4. It was positioned at 160cm from the floor to the centre of the panel. It has a measured colour temperature of 3179K and incoming light brightness was measured in the range 1900-2070 lux at the surface of each panel. The spot light used was the Arri ST1. It was positioned 182cm from the floor to the centre of the filament, has a measured colour temperature of 3160K and incoming light brightness range was 5660–5800 lux at the surface of each panel.

The camera is capturing at 50Hz, 1/100 Shutter speed at ISO 100. White balance is set to 3200K and footage shot in 4k resolution. A Zeiss Milvus 28mm lens was chosen to fit the LED panel in frame, and the aperture set to F4. The wall brightness was set to 1371 nits and white balance set to 3200K to match the camera. In each case, the footage of the panel was cropped so the equivalent region of the LED panel is in frame and Rec 709 LUT was applied to the HDR footage. The histogram information was then extracted from Kdenlive [12]. The results can be viewed here: https://youtu.be/_Rfu3vppcIg and are discussed further in Section 3.1.

2.3 Grazing Angle

A comparatively unsophisticated experiment was used to assess the affect of increasing the grazing angle. The camera was positioned parallel to the wall, with the sensor centre approximately 40cm from the panel. The result is shown in Figure 6.

We observe that the AOTO panel does not use a mask or gel coating (see Figure 1), allowing more of the bulb can protrude from the panel. This, coupled with a custom LED design leads to a greater grazing angle range than the other panels tested [20].

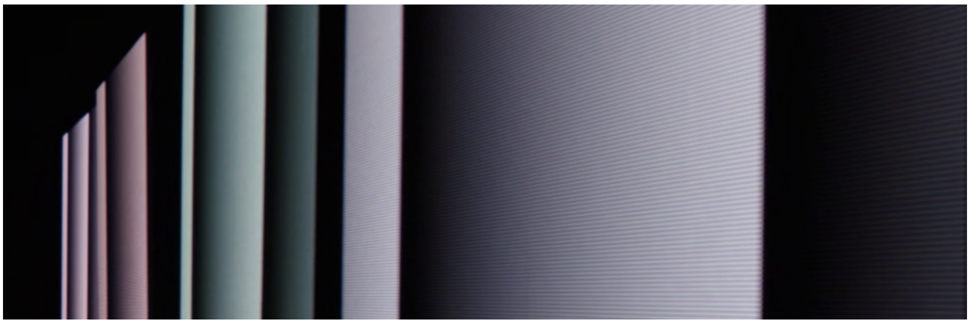


Figure 6: The four panels at a viewing angle of approximately 160°-170°. From left to right: ROE Ruby 2.3, ROE Black Onyx 2, AOTO RM2.3 and Absen PL 2.5.

While our result does little more than confirm the stated viewing angle in the published technical specifications, it does provides a sense of the impact of extreme viewing angles on colour and brightness. In practice it is clear that practitioners should be filming as orthogonal to the screen as possible to avoid both grazing angle and Moire artefacts.

3 Results and Recommendations

3.1 Colour Reproduction

LED's are sorted according to brightness and colour gamut using a process referred to as "binning" [1, 11]. A colour calibration chart is used to define the colour range the panel is able to approximately achieve, which is used by the controller for dynamic calibration. However, even if each panel is instructed to achieve the same colour by the controller, do the panels actually output the same colour?

Colour meter readings were taken from the different panels displaying pure green in Rec 2020 in the achievable range with the house lights off. Brightness was set at the default 1371 nits and colour temp set at 3200K. Colour reproduction was also visually compared with a ASUS ProArt PA32UCG monitor.

Ruby 2.3 | Black Onyx 2 | AOTO RM2.3 | Absen PL2.5

Figure 7: A comparison of light meter readings from the different panels displaying pure green in Rec 2020 in the achievable range.

Fig 7. The ROE Ruby and AOTO RM2.3 have comparable sharp peaks on the green spectrum but have a noticeable blue bump. The ROE Black Onyx 2 is registering an orange bump. The Absen peak is less sharp than the Ruby or AOTO panels, but there are no secondary peaks. Note that there was very little discernible difference when displaying red and blue across the panels.

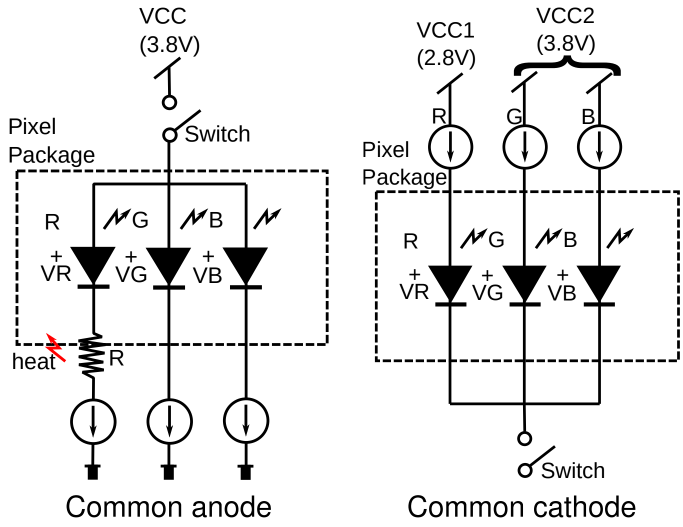


Figure 8: The two most common methods for powering the individual LED components. In common anode, excess voltage is dissipated as heat, whereas in common cathode, a separate supply is used to power the red channel. Image courtesy of [19].

A crucial observation is that although the controller is issuing the instruction to all panels to reproduce the same colour, the output colours vary significantly according to the measurements, the eye and the camera. This is an important measurement and should be performed on sample panels from a particular batch to ensure colour reproduction meets with the standard required for the usage scenario.

It is also important to note that due to the binning process, conclusions cannot be inferred for all panels from the particular manufacturer as the LED's sorted according to their properties for each individual batch. What can be said is that it is essential for all panels used in-camera to originate from precisely the same batch. For this reason, manufacturer assurances relating to how LED's are sorted kept aside for future purchases should be considered in purchasing decisions.

Due to time constraints, our colour evaluation is very limited — it has been suggested that a thorough colour evaluation should evaluate a range of colours at different brightness levels [15].

3.2 Common Anode vs Common Cathode

Panel design is complex, requiring the combination of multiple technologies to meet customer demands to provide a product at a competitive price point. At the level of each individual LED there are panel design decisions which directly or indirectly influence the power consumption of the overall panel.

Power consumption is directly affected by the way the LED is connected to the board. A design constraint in LED panel manufacture is that the voltage for the red LED is slightly lower than the blue and green LED's (2.8V vs 3.8V), which can be resolved during manufacturing in three ways:

- Common anode is the most common approach which sends the same voltage to each LED, but dissipates excess voltage as heat.
- The alternative common cathode process allows a different voltage to be sent to red, resulting in an 10-15% reduction in power requirements, but due to the low efficiency of dual voltage power supplies the saving may be as little as 5% [15].

These two different approaches are demonstrated in Figure 8. The main reason for choosing common anode over common cathode in contemporary panel design is cost, and given that other efficiency factors may mask the effect of common anode it is still widely used.

3.3 LED Brightness

If an LED can achieve a greater brightness, it uses less power to achieve the same brightness as a dimmer LED. The relationship between brightness and power consumption is almost linear. Increasing the brightness of individual LED's could be achieved in a number of ways:

- Brighter LED's could be separated during the binning process (see Section 3.1), or a larger chip could be used. While this will directly impact on the price of the LED, the power consumption will typically be 15–20% less for equivalent package size and brightness.

- LED's can also divided into either white or black varieties, determined by the colour of the LED and the epoxy lens. White LED's are much brighter and typically use 20-25% less power than the black LED alternative. For a good contrast, white LED's can only be used at a pixel pitch of 5mm and above, which makes them unsuitable for in-camera VFX. For this reason white LED's are typically used on studio ceilings but not on in-camera panels [15].

- Flip chip is a newer manufacturing process, which eliminates the welding of gold or copper wires to the top of the dies. This frees up to 30% of the LED top surface. The cathode and anode are on the bottom side of the LED and are connected to the carrier [15]. This can increase brightness by 30-40% in comparison with wire bonded LED and boosts contrast by increasing black surface area while allowing a higher density of LED's on the board. While this technology obviously has many advantages it has several limitations:

  - The bond is weaker than wire bonded LED, making the panel slightly more fragile [19],
  - When using flip chip with Chip on Board (COB), it is not possible to use the binning process to light individual LED's to help control colour and brightness uniformity tolerance as you are only able to light pixels once thousands have been added to the circuit board [19].
  - It is considerably more expensive than other manufacturing processes due to the increased size of the die [15].

  For these reasons this technology has not yet been widely adopted and there is still widespread use of common anode and common cathode.

In summary, it is possible to design a panel for virtual production which could reduce power consumption of 50-60% when compared with a standard common anode approach, but this needs to be balanced with other priorities such as colour / brightness range, uniformity and cost.

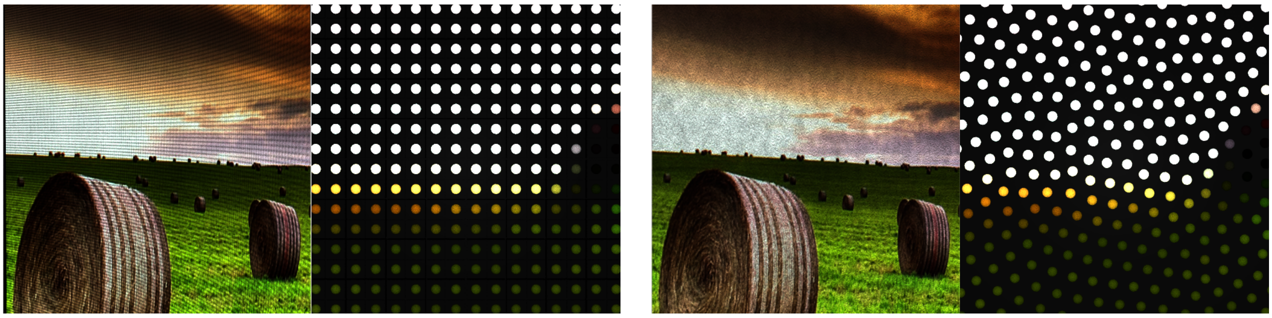
3.4 Moire Artefacts and Pixel Layout

The filming of an LED wall is effectively the process of projecting a grid of pixels onto a camera sensor with a grid layout. The resulting Moire artefacts are entirely predictable when the camera resolution exceeds the projected image of the wall, and exacerbated by lens distortion and transformations.

Figure 9: A comparison of half–toning techniques used in printing grey-scale images. Methods which diffuse samples according to a density function avoid noticeable patterns. Reproduced from Ulichney [18].

There is wide evidence that the layout of pixels in the display and the sensor has a significant impact on the captured image. Sample distribution strategies in printing (Fig. 9) are widely used due to their ability to reduce visual artefacts. Lanaro et al. [10] showed that the distribution of features of a human retinal cone can be well described using blue noise sampling. Applying this logic in the context of Virtual Production leads to two possible mitigation strategies:

1. modify the sampling strategy of the CMOS sensor, or
2. alternatively change the pixel layout of the LED panel.



(a) (b)

Figure 10: The synthetic uniform panel from Figure 2 (in (a)) is compared against a blue noise distribution of pixels generated through Lloyd's relaxation.

In Fig. 10 we evaluate (2), modelling and rendering an LED panel using a scattered pixel distribution, demonstrating (in the synthetic case at least) the alternative pixel layout eliminates the Moire effect. In order to test (1), alternative Debayering filters could be evaluated in order to influence the presence of Moire, for example the method of [3].

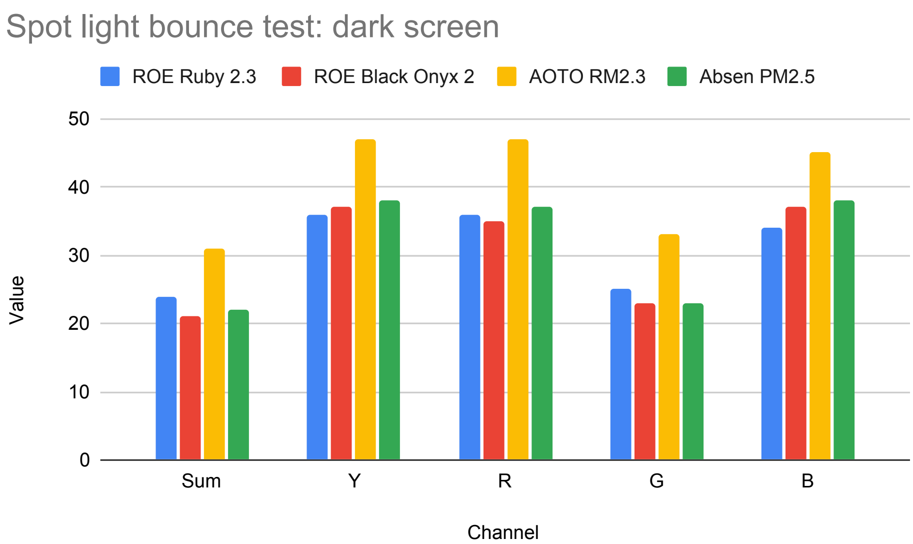


Figure 11: A histogram visualisation of the footage taken from the spot light bounce test on the black screen. The histogram was generated from footage (`https://youtu.be/_Rfu3vppcIg`) and the cropped frame analysed using Kdenlive [12].

3.5 Measuring Contrast

The contrast ratio was defined by Winter [19] as "the ratio of maximum brightness to minimum brightness under certain ambient illumination." The contrast ratio of an LED panel is a divisive subject

— currently there are no accepted standards for defining ambient illumination or agreed method for measuring brightness. Certain panel manufacturers, for example, register extremely high contrast ratios by defining the black level under unrealistically low ambient lighting conditions [15]. For this reason, ROE regularly refuse to provide contrast values to customers as they have little meaning if they are not measured under equivalent experimental conditions.

In the experiment already described in Section 2.2 we independently created a contrived scenario for measuring the light reflectance off the panel using studio lighting, which is very similar to the manner in which contrast ratios might be evaluated by manufacturers [15]. A noticeable difference was detected during the soft light bounce test off the black screen (see Fig. 11) in the AOTO panel, which could be explained as higher reflectance of the disabled LED than comparative panels at the tested incidence angle [15]. However, it is generally difficult to draw comparative conclusions between the panels with respect to contrast ratio.

In film production, Technical Visualisation (TechVis) is the process of identifying, planning and modelling the technology used for building complex production scenarios. This includes camera type, lenses, rigging, virtual and physical set building and stunt planning. To our knowledge, Virtual Production studio planning does not currently include modelling of LED build simulation, taking into account colour reproduction, shooting volumes and ambient illumination under studio lighting conditions. However this level of accuracy would help in both design and procurement decisions.

In Computer Graphics, the process of generating an image is governed by the Rendering Equation [9], which at a high level integrates the interaction of lighting and geometry in the scene. The reflectance of light from a surface (or subsurface) is described by a bi-directional function which determines the proportion of light reflected from the surface at a point given an input direction and an output direction. Panel geometry incorporates grooves and / or masks about the pixels to enhance the contrast (see Fig. 1), which impacts on how light is reflected from the panel. At a macro level, the panel material between LED's could be expressed in the form of general reflectance distribution data or an appropriate functional representation, which could be incorporated into a rendering model. This would allow the modelling of indirect studio lighting on the rendered output of the panel, not only assisting in procurement decisions based on usage but also influencing lighting design during Technical Visualisation stages.

Measured emission patterns were provided by the panel manufacturers in the X and Y directions, sometimes split between colour channels. This information can be used to deduce the impact on grazing angles, but also might be used to explain colour separation in Moire artefacts. For the results in this paper we created a radiation map by interpolating the cross–sections with a radial pattern, yielding the radiation map shown in Fig. 12(d), which is used in the synthetic results (Fig. 10).

More holistic measurements of LED emission patterns would support better simulation of the panels for TechVis purposes — we would recommend the publication of LED emission patterns using known photometric standards, such as IES 2018 [7], which is supported in commercial rendering software (for example, Arnold [4]).

4 Summary

In this paper we evaluated four LED panels from three vendors for use in Virtual Production using experimental conditions. We designed and implemented three principle tests to evaluate these panels for Virtual Production applications:

1. It was hoped that the **orthogonal track test** (Section 2.1) would reveal differences between the panels in terms of Moire and scanline artefacts on a range of test images. Unfortunately no discernible difference was visible, although this test was the most time consuming.

2. The **light reflectance test** (Section 2.2) measured the radiance of reflected studio lighting on the LED panels. Some variation in the panels was detected (see Fig. 7) leading to our recommendation that a bidirectional reflectance function would be useful as this would capture all possible lighting scenarios (see Section 3.5).

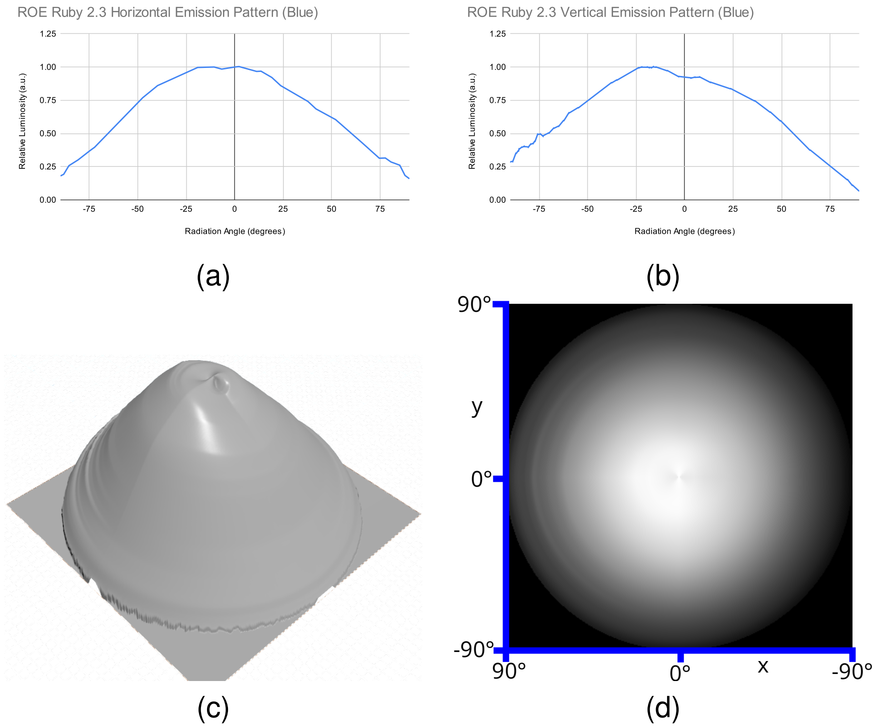


Figure 12: The manufacturer [15] provided emission patterns ((a) and (b)) are lofted into a surface (c) assuming a radial interpolation method. This is converted into a heightfield image (d) which can be used during rendering in shading calculations. Only the emission patterns for the blue output are shown, but the same treatment is applied to the other colour channels.

3. While not strictly a test, we evaluated the filming of the panels at a 70-80° **grazing angle** to the orthogonal. If anything this test confirmed the manufacturers advertised panel specifications, although (as discussed in Section 3.5) publishing detailed emission patterns would allow better planning for production scenarios.

Based on these experiments and information provided by the manufacturers, we have a number of recommendations to better support the use of LED panels in Virtual Production:

- Colour reproduction is very important, and influenced by manufacturing decisions (e.g. binning). It is a well–understood practice to replace panels from a set from the same batch to ensure consistency. It would behoove any procurement team to investigate samples and (ideally) measure the colour reproduction in order to ensure it is appropriate for a particular application (see Section 3.1).

- Manufacturing decisions greatly influence the brightness and cost of LED panels. Brighter panels need less power to achieve equivalent brightness, so power draw could theoretically be cut significantly by choosing alternative manufacturing approaches or selecting LED's based on brightness (see Sections 3.2 and 3.3).

- By modifying the layout of pixels on the display, or adjusting the sampling strategy of the camera, Moire artefacts could potentially be eliminated altogether (see Section 3.4), although the manufacturing and rendering complexity of doing this have not been considered in this paper.

- By publishing both the reflectance distribution function of the back panel and emission patterns of the LED's, manufacturers would allow studio planners to accurately simulate the panel and lighting design of a virtual production studio (see Section 3.5), eliminating the need to publish the contrast ratio.

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