ADVANTAGES AND CHALLENGES OF SHOOTING FILM IN AN LED- VOLUME

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Abstract: One of the latest technologies to arise in the film industry are so called LED-volumes, a term which refers to studios with LED- walls allowing for virtual backgrounds and effects to be projected on set in re-al-time. This type of virtual production offers filmmakers to see the final image being composed even on set, opposed to imagining it when shooting on green screen. Still, the technology doesn't come without limita-tions, some of which are bound to the nature of digital rendering and risk images shot in LED-volumes to look rather synthetic. This limits the use case in several ways.

As LED-volumes are deemed to be the future of filmmaking and increasingly more productions are making use of it, finding ways to eliminate the technical drawbacks to increase creative freedom becomes of great importance in the industry. In this thesis, I will discuss whether shooting on celluloid film in LED- volumes, op-posed to shooting on digital cameras, can reduce digital image characteristics and thereby increase creative freedom in the cinematography.

For this purpose, both analog and digital test footage is shot as a conceptual proof of the advantages and challenges involved. The acquired knowledge is then applied in a narrative production in an LED-volume and the practical implications are analyzed with the help of industry professionals. Based on this comparison, it was found that celluloid film partially reduces undesired digital image characteristics but complicates the workflow in both preproduction and on set, mainly due to a lack of reliable on-set monitoring.

Based on these findings, future productions can take precautions and adjust their workflows to suit the yet uncommon production conditions.

PREFACE

In the past three decades, the world of filmmaking has been transforming to an increasingly digital one. From cameras to post-production workflows to the delivery in either cinema or online streaming-services, almost the entire pipeline has been digitized.

In this digital era of moviemaking, the question of practicality of the former state of the art, traditional celluloid-film, arises. As time moves on, fewer productions shoot on film which leads to it becoming more costly and harder to come by because the infra structure behind film seems to shrink constantly. With the increasing quality of digital cameras on the other side, it seems like less and less arguments can be made for shooting on film.

Can film therefore be considered obsolete by now? Or should it be considered as just another tool in the box that might still have its place in the right occasion? And if so, where would that be? Is it a purely creative choice for a specific look or work ethic on set, or is there still a measurable merit to it?

In March of 2023, I attended the Virtual Media Lab Conference at Stuttgart Media University. International guests and speakers discussed the technological change in the film industry with a focus on LED- Virtual Production. With what I had learned at the conference, the idea for combing the newest and the oldest tool in the industry, the LED-volume and celluloid film, had sparked. Could the LED-volume be the place for analog film, countering the often synthetic look and reducing digital image artifacts?

One of the only productions to date that has made larger use of analog cameras in virtual production environments is HBO's Westworld- season 3 (2020). Since this combination of tools is highly expensive, technically complex, and therefore uncommon, I was curious to investigate upon the practicality of film in LED-volumes.

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1. INTRODUCTION

Movies have been made for over a century. During this time span, the medium constantly evolved and was reinvented by new technologies paving the way for new cinematic possibilities. The expansion from silent movies to sound films in the 1920s e.g., revolutionized filmmaking. On the one hand, sound freed the visuals as the story didn't have to be fully understandable by the images only, but could be carried by the sound, too. The camera could concentrate more on the aesthetics of a scene or create an overall mood instead of plainly showing the action.

On the other hand, the newfound sound challenged the cinematography and staging. As the microphones of the time didn't deal well with wind, they couldn't be moved and had to be installed fixed in the studios. This reduced the range of movement of the actors because they had to keep the right distance to the microphones. Actors not moving around as much also affected the movement of the camera as it became more static. Also, film not only being a visual medium anymore, synchronization and subtitles were required to make movies globally comprehensible. (Josse, 1984, p. 290).

Even Today, the medium is evolving with ever new possibilities and challenges simultaneously. In the past few decades, digitalization brought forth new cameras and tools for digital postproduction, including editing software, image and sound manipulation software as well as computer animation or so-called computer-generated-imagery (CGI) (Daly, 2009, p. 2-3). This has led to never-before seen virtual worlds, effects, and animated creatures.

All these digital tools and processes are often promoted to provide unlimited creative freedom. Yet, none of them truly do. In the digital world, this is often bound to limited computing power and the sheer time available to realize an idea, whether it be on set or in postproduction.

One of the latest digital tools to arise in the industry are so called LED-volumes, a term which refers to studios with walls made of led panels that project digital backgrounds and effects on set in realtime. For the director and DP, this has the advantage of being able to see the final image in camera, opposed to imagining it when shooting in a green screen studio. The crew can react to the virtual environment on set, thus adjusting production design, lighting, framing, and staging to fit the background, instead of stitching the image together in post (Kadner, 2019, p.7).

Still, this method doesn't come without compromise as I will discuss in detail in this thesis. As I will lay out, most of its drawbacks are of digital nature, like latency, color rendition aswell as digital image artifacts (Kadner, 2021, p. 61- 62). This limits creative freedom with the camera in several ways. So just like the switch from silent- to sound film, there is a duality in the affect it has on the way filmmakers can capture images, with the creative freedom being directly linked to the technical framework used.

This method of shooting is often deemed to be the future of filmmaking. As LED-volumes rise in popularity and increasingly more productions are making use of it, finding ways to eliminate the technical drawbacks to increase creative freedom becomes of great importance to filmmakers. This means either developing new tools or finding ways to combine conventional tools in new ways.

When talking about limiting properties of digital camera systems, one tool that comes to mind, ironically, is celluloid film. Could film with its analog characteristics minimize or even eliminate these digital flaws or does it come with even more technical difficulties as one has to find ways to integrate an analog system in an otherwise entirely digital workflow?

In this thesis, I will discuss whether shooting on celluloid film in LED- volumes, opposed to shooting on digital cameras, can increase creative freedom in the cinematography. I will first theoretically lay out the technical parameters behind the question and explain the advantages and challenges film might provide. I will then go on to shoot footage in industry standard conditions and evaluate the practical impact they have on a production.

The goal of this thesis is not to delve to the bottom of every one of the technical topics relevant, since this would be beyond scope, but rather to showcase the workflow as a whole and answer the occurring questions with as much depth as practically relevant.

2. THEORY

2.1 Definition of LED-volumes

LED-volumes or volumetric studios are a type of virtual production environment. The term virtual production (VP) refers to several computer-based media production methods. These methods are realized using a combination of augmented reality, virtual reality, CGI, and game-engine technologies. According to WETA DIGITAL, “Virtual Production is where the virtual and physical worlds meet” (Kadner, 2019, p. 3). Besides LED-volume virtual production, this also includes green screen virtual production with real time compositing, often used for pre-visualization or in live broadcast (Sony, 2022, p. 3).

The essential concept of the LED-volume is to surround physical props and actors with a virtual scene that is displayed on an LED-wall in the background. In

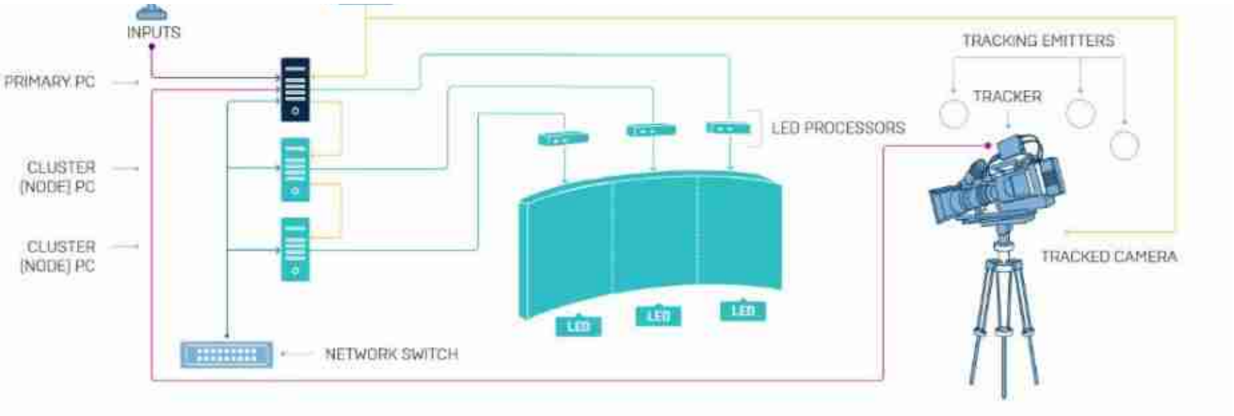


FIGURE 2.1.1: Methodical organization of an LED-volume

contrary to traditional green or blue screen production, this allows production crews to see the scene being composed in real-time on set. It is therefore called in-camera visual effects (ICVFX) (Sony, 2022, p. 3).

In the figure 2.1.1 above, a methodical organization of an LED-volume can be seen. There are different configurations of LED-volumes. Whereas big productions like The Mandalorian, one of the first shows to make extensive use of the technology (Kadner, 2021, p. 3), were filmed in a 270-degree oval shaped studio with curved LED-walls and an LED ceiling, there are also smaller studios with a singular, flat wall. No matter the size of the Studio, the technical components involved fundamentally stay the same.

The studio consists of an LED-Wall, itself usually being a matrix of several LED-panels, made up of LED-pixels. These pixels consist of 3 LEDs each, emitting red, green, and blue light. The distance between the pixels is called pixel pitch. The pixels are run by processors receiving the image information from a computer workstation via HDMI, Display Port or Ethernet. The system consists of a primary PC and several cluster node PCs and is called Brainbar. It runs a virtual 3D- environment based on a computer engine like Unreal Engine, which is the most common one. These computer engines used don't only render 3D models but also logical parameters like laws of physics. Complex environments with realistic behavior of light can be simulated (Kadner, 2021, p. 4). The virtual camera in Unreal dictates the perspective of the virtual environment that is being rendered in real-time and sent to the wall to be projected.

The physical camera on set is being tracked and the virtual camera matched to that tracking data. This has the effect that when the real camera is panned, tilted, or moved in any other way, the virtual camera simulates the movement in the virtual environment and the perspective on the wall shifts accordingly (Kadner, 2021, p. 25). This allows for accurate parallax which is the crucial difference to traditional rear or front projection, where the projected background plate is either pre-filmed or pre- rendered and therefore can't react to the camera movement. This fundamentally limits the possible camera movement and angle, without the projection being noticeable (Kadner, 2019, p. 17- 18).

To seamlessly display the illusion of a real background for the camera, all components involved from rendering to displaying must be strictly synchronized. On a software level, this means the PCs running the virtual environment should have the content ready simultaneously. On a hardware level, the display swap, which is the switch between the current image to the next one on the wall must be in rhythm with the shutter of the camera, thus the moment the image is captured, to prevent tearing artifacts in the wall. This is achieved with a synchronization signal like Genlock that keeps in the components running to the same pulse (Epic Games, 2019, p. 8).

The ability to see the virtual set extension being projected in real time changes the traditional on-set workflow. Designated Unreal artists, compositors, IT experts and technicians work together with the departments to discuss the content on the wall and technical aspects, since the virtual set extension effects the work of several departments involved like production design, camera, and lighting (Kadner, 2021, p. 53- 54).

2.2 Light and Human Perception

The behavior of light can be described using two different models: light as a photon and light as an electromagnetic wave.

Before going into further technical details of different camera systems, we first need to understand the fundamentals of human perception. For this purpose, I will use the model of the electromagnetic wave.

The perception of color depends on two main factors. One being the objective, physical variables wavelength and energy and the other being the subjective spectral sensitivity of the observer in relation with the interpretation of this stimulus (Evans, 1971, p. 12- 13).

The parts of the human eye relevant for sight are the cornea, the pupil, the lens and the retina. The cornea and the lens allow for the surrounding to be projected on the image plane, the retina. The pupil works like an aperture, reacting to the brightness and regulating the amount of light entering the eye. On the retina, there are two types of photo receptors, the rods and the cones. While the rods are responsible for scotopic vision, meaning vision in low-light situations and therefore more sensitive to luminance but don't render colors as vividly, the cones, being active in bright surroundings, are sensitive to colors. There are three types of cones in our eyes, sensitive to blue (short wavelengths), green (medium) and red (long). Figure 2.2.1 below shows the sensitivity curves of the cones. As can be seen in the graph, all cones cover a range of wavelengths or colors, but peak in the respective primary color. (Ashe, 2014, p. 11-12).

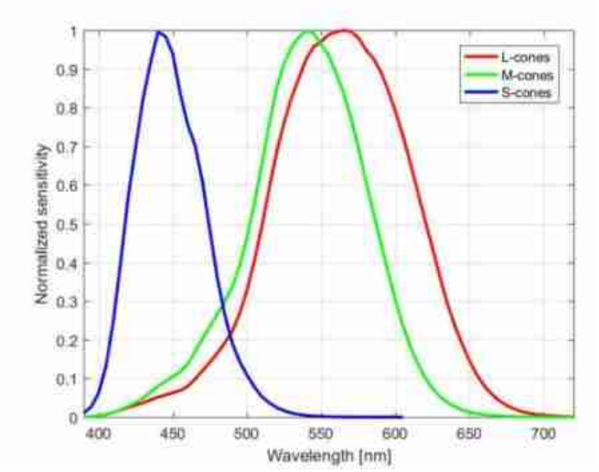


FIGURE 2.2.1: Spectral sensitivity of human cones

Depending on the wavelengths in relation to the intensity (the spectral power distribution) of the light hitting the retina, the cones will respond accordingly, and the signals will be interpreted by the brain as a specific color. The stimulus of these 3 primary colors is sufficient to render every color in the spectrum between 380- 780 nm (Schmidt, 2013, p. 69). Figure 2.2.2 below shows the spectral power distributions of several common light sources. The color shifts along the x-axis represent the respective human perception of the wavelengths.

Whereas daylight has a "broad" power distribution, with relatively even intensity along all wavelengths perceptible by the human eye, incandescent light leans heavily towards the red end of the spectrum. This results in daylight being perceived as white or neutral and incandescent light as warm or orange. Fluorescent light on the other hand has narrow spikes in the green and orange range of wavelengths and gaps in the short wavelengths and is therefore perceived as warm with a greenish tint. When being exposed to a lighting situation over a longer period, the eyes will adapt not only to brightness but also to the average chromaticity of the stimulus by balancing it towards white (Giorgianni & Madden, 2009, p. 27-28).

An object illuminated by white daylight can either absorb or reflect wavelengths of light. An object is perceived as orange, e.g., because it primarily reflects wavelengths of 580nm while absorbing others

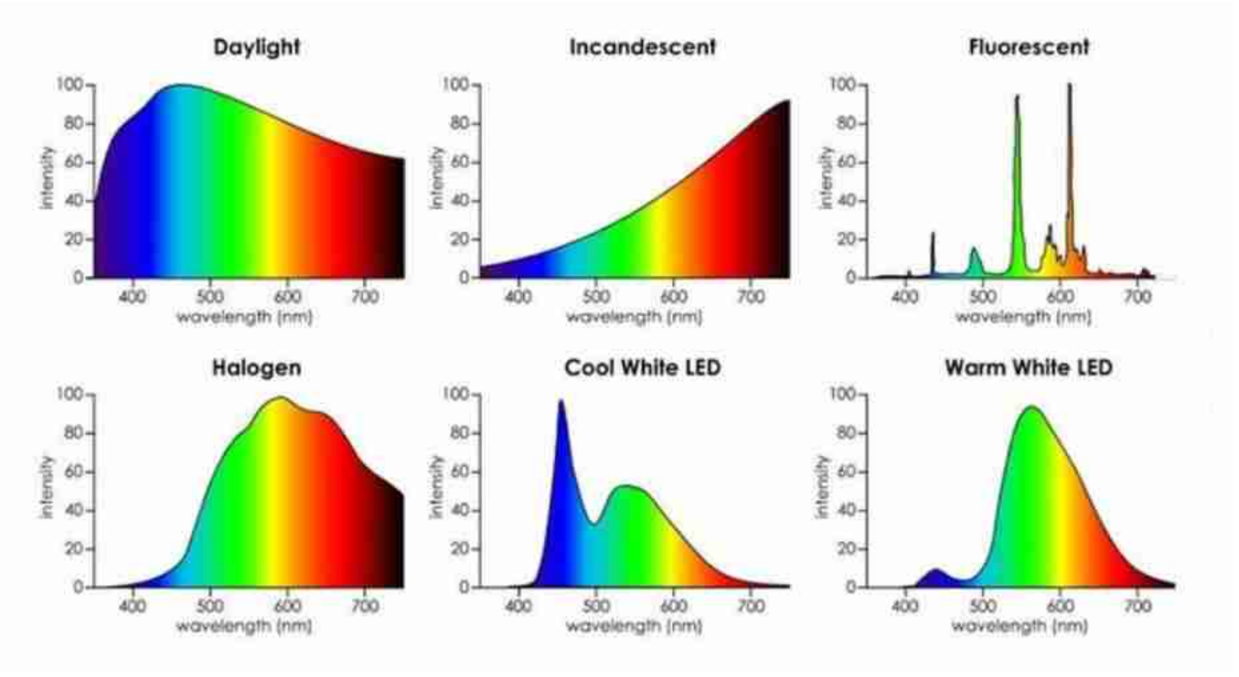


FIGURE 2.2.2: Spectral power distribution of common light sources

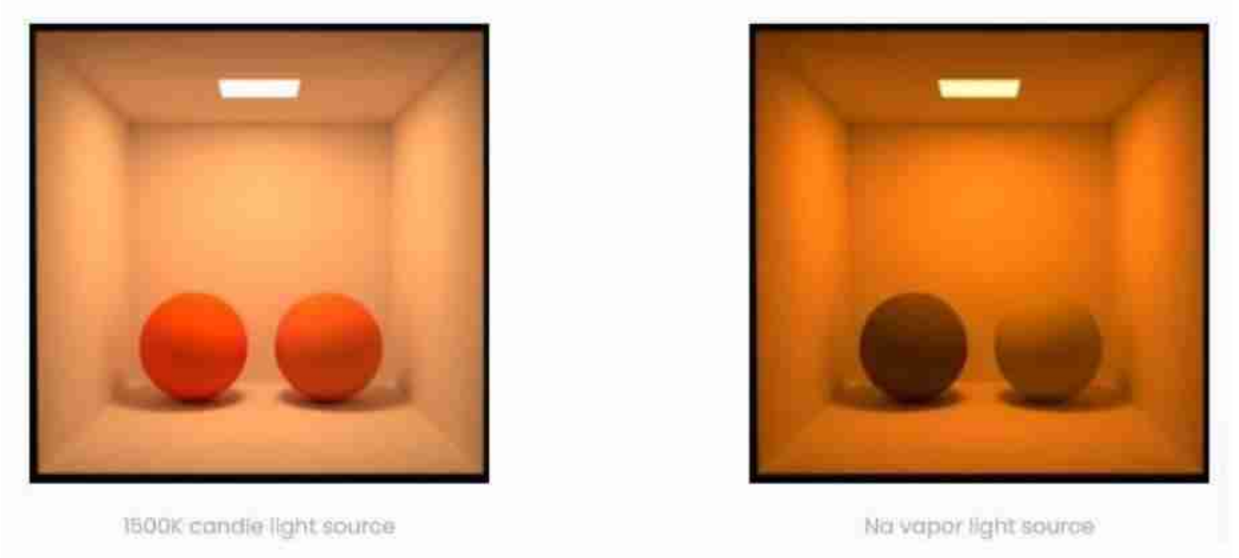


FIGURE 2.2.3: visual metamerism test

(Ashe, 2014, p. 9), while a second object primarily reflects wavelengths of 650nm and is therefore perceived as red. When being illuminated by a source with differing power distribution on the other hand, the reflected color will differ, since the lack of emitted power from a source for a certain range of wavelengths doesn't allow for a surface to reflect those. The color reflected of the two objects might match under one light source while differing under another. This phenomenon is called metamerism and it is bound to trichromatic vision, producing a color as an additive mixture of only red, green and blue (Giorgianni & Madden, 2009, p. 9) (Ashe, 2014, p. 16-17). In figure 2.2.3, the scene was illuminated with two different light sources.

Figure 2.2.4 shows two differing spectral power distributions producing equivalent color stimuli. This is called a metameric pair. The perception of color will be different for every person, depending on several factors such as sex, age, ethnicity and so on. Whilst one observer might render two color stimuli identical another might not. This is called observer metamerism (Giorgianni & Madden, 2009, p. 31)

When generally referring to human color vision, the CIE "Standard Observer" from 1931 is usually referenced. It's also the basis for color standards in motion picture imaging (Stump, 2021, p. 53).

The point of equal energy is perceived as white, and it lies at 0.33/0.33. Each hue can be resembled as a straight line from that point outward, with increasing saturation to the edge of the so-called horseshoe (Schmidt, 2013, p. 75). The color space resembles and quantifies all color stimuli perceptible by humans, however, not color perception since this is largely subjective. (Giorgianni & Madden, 2009, S. 28).

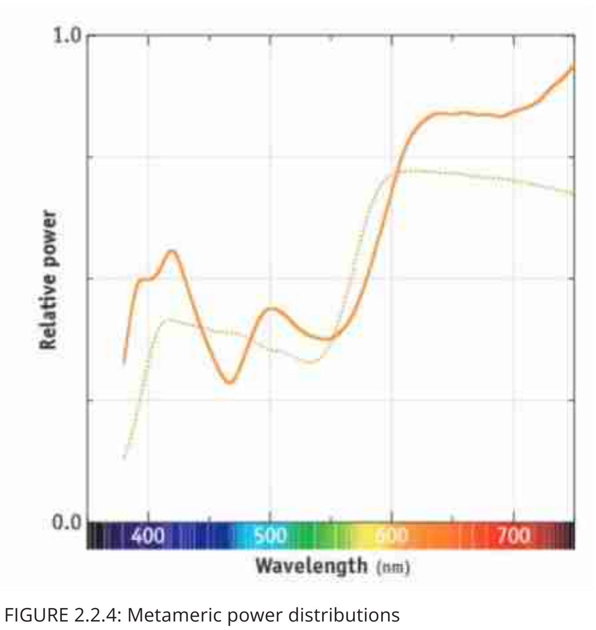


FIGURE 2.2.4: Metameric power distributions

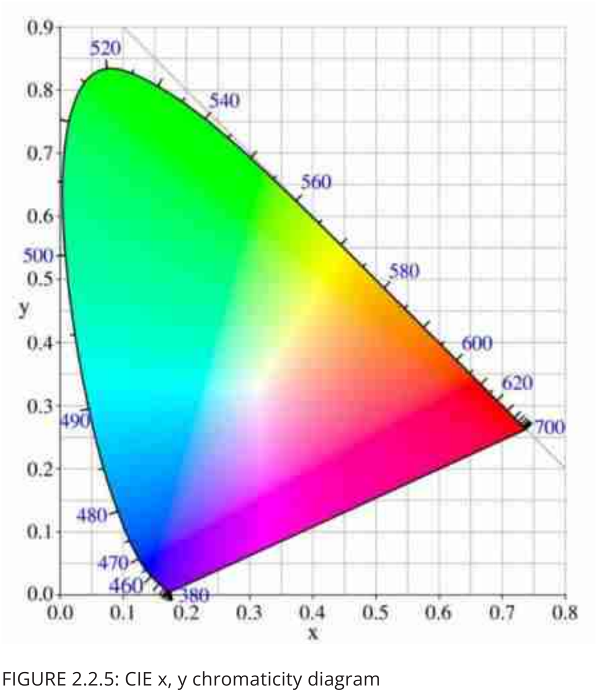


FIGURE 2.2.5: CIE x, y chromaticity diagram

2.3 Technical Comparison of Film and Digital
2.3.1 Crystals and Sensels

Just like the human eye, both film and digital sensors are sensitive to the three primary colors red, green, and blue. However, the nature of the reaction to exposure and the spatial distribution of the photo sensors differs. (Giorgianni & Madden, 2009, p. 19)

On film, light is captured as a photochemical reaction of so-called silver halide crystals which react when being exposed by blackening and becoming in transparent. They are embedded in an emulsion of gelatine and distributed stochastically, meaning in irregular patterns. To render color information, several of such emulsion layers overlay, each of which being sensitized to absorb the wavelengths of one of the primary colors. When the film negative is exposed to light, the photons first travel through a protective layer and a UV filter layer, protecting the emulsion layers from scratches and preventing the emulsion layers to react to UV-light, to simulate human sight, which isn't sensitive to UV light rays aswell. The crystals in the first two emulsion layers are sensitized to absorb blue light. All light that travels past these blue-sensitive layers is being filtered by a yellow filter layer to ensure that none of the prevailing blue light rays enter the green sensitive layer underneath. The same principle applies for the following layers (Schmidt, 2013, p. 298-299). To prevent light from being reflected on the film base back into the emulsion layers and causing secondary exposure showing as halation around the highlights in the image, an anti-halation layer, or so-called rem-jet layer, on the back of the film is coated black (Kodak, 1996, p. 44). These layers sit on the film base, the carrier material.

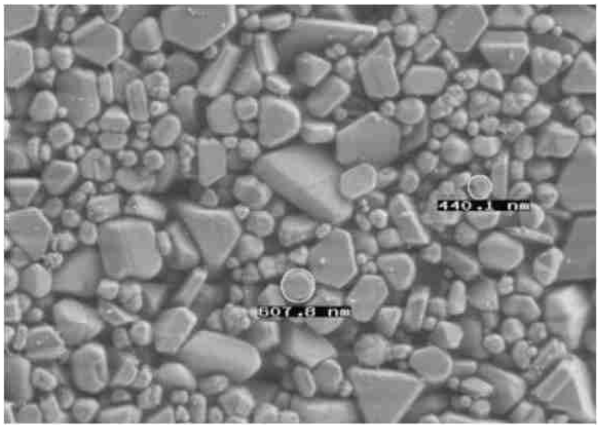


FIGURE 2.3.1: Silver Halide crystals under the microscope

The larger these crystals are, the more sensitive they are to light because of their increased surface area. This means the higher the ISO or the "speed" of the film, the more noticeable the crystal structure will be for each frame and the "grainier" the image will appear. (Schmidt, 2013, p. 314)
The exposed film then captures a latent image with inverted luma information because the brightest areas in the captured scene are rendered the darkest or least transparent on the film, hence the name negative film. Sealed off from light to prevent further exposure, the negative is sent to the lab to be processed. During the processing stage, colored couplers in the emulsion layers chemically react and cover the crystals in the respective complementary color which they absorbed, the intensity of color depending on the captured light intensity during exposure, while the transparency is being inverted. The remaining color negative is now either scanned to go through digital postproduction or projected onto a positive film (called printed) that inverts the colors yet again to create a print film, with positive transparency and colors and increased contrast, ready for projection (Schmidt, 2013, S299- 300).

Because this crystal pattern is irregular and different for every frame, film renders images anisotropic. Practically speaking it has the effect that a straight line will be rendered with differing deviation for each frame (Stump, 2021, p. 21). This characteristically analog texture, to a certain degree, is a desired texture for a lot of filmmakers (Kenneally, 2012, 00:07:39-00:08:12). It is often said to give the image a natural, organic look. Even when shooting in digital, which doesn't create grain texture in the image, film grain is often simulated digitally in postproduction to reproduce this analog look and feeling.

In digital cameras, light is captured as a digital signal, meaning numeric code value, via a sensor. Most modern digital cinema cameras utilize a sensor technology called CMOS (Complementary Metal Oxide Semiconductor). In CMOS sensors, electronic photosites collect photons of light for every frame, to meter light intensity. These so called sensels (sensor elements) are organized in a grid. When being exposed, the sensels transmit voltage according to the amount of photons captured that is then interpreted into discrete numbers by an analog- digital converter, producing the digital value of each sensel. Every photosite can only capture so many photons until it reaches full-well-capacity and "clips". This is being rendered as full saturation or white. The information of any more light intensity is lost. (Stump, 2021, p. 19).

These sensels are naturally equally sensitive to light of all wavelengths. To capture color information an

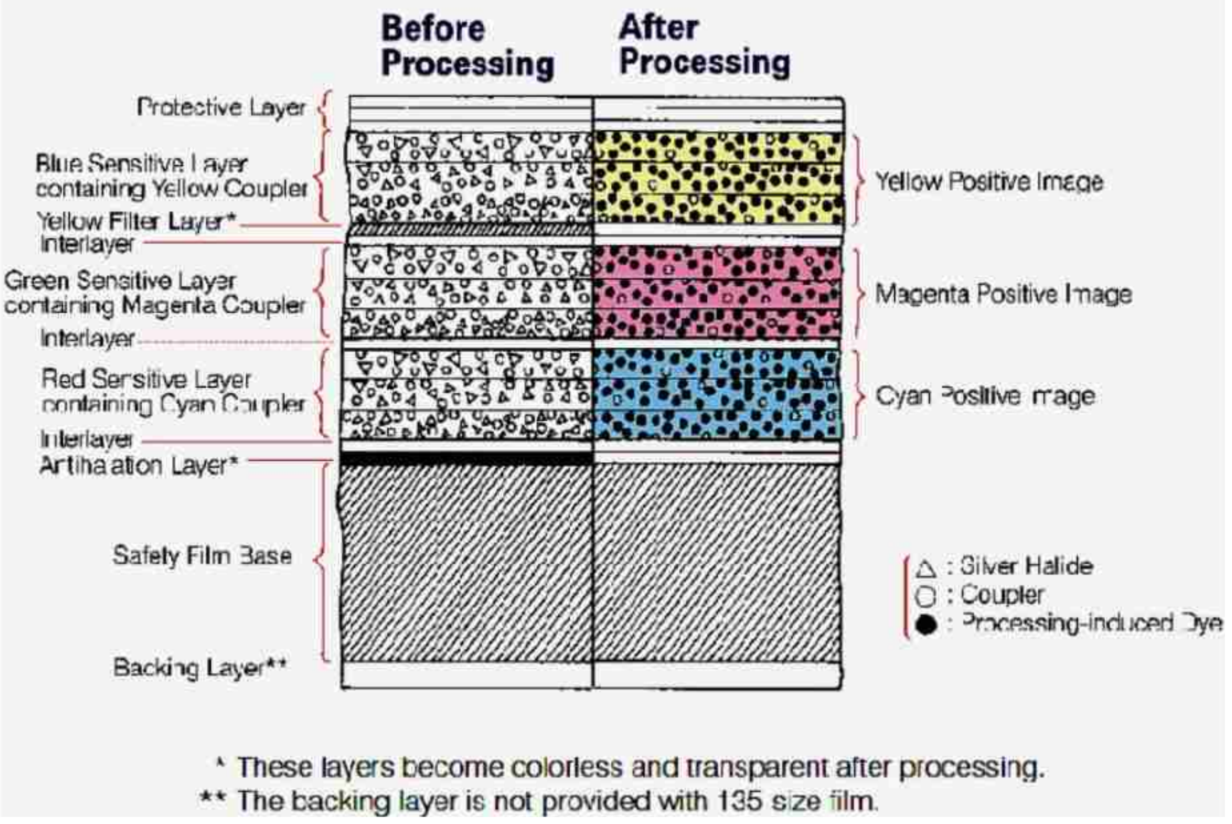


FIGURE 2.3.2: schematic film layers

array of color filters in front of the sensels separates the light into the three primary wavelengths. That way, each sensel only captures light information for either red, green, or blue. This results in a mosaic-like grid pattern. Hardware manufacturers arrange these filter arrays in numerous ways. To calculate the RGB values of each pixel, digital values of several adjacent sensels are interpolated. This is called de-mosaicing. The algorithm depends on the filter array and the manufacturer. In figure 2.3.3 below, the most common pattern, called bayer-pattern, can be seen (Schmidt, 2013, p. 380).

Because the sampling of colors happens side by side in a periodic gridpattern instead of overlaying layers like on film, or irregularly like in on the retina, color sampling errors occur. This shows as color fringing when a line or the edge of an object is sampled across a line of only 2 alternating colorpatches on the mosaic and misses the information of the third color. Even after de-mosaicing, the colorfringing would prevail. Camera manufacturers place an optical low pass filter (OLPF) in front of the filter array to spread the light coming through the lens to let the different colored photosites receive a more average amount of color from the scene. The degree of diffusion from the OLPF is calculated so the image loses minimal sharpness while minimizing the sampling errors (Stump, 2021, p. 30). This is explained in further detail in chapter 2.3.3.

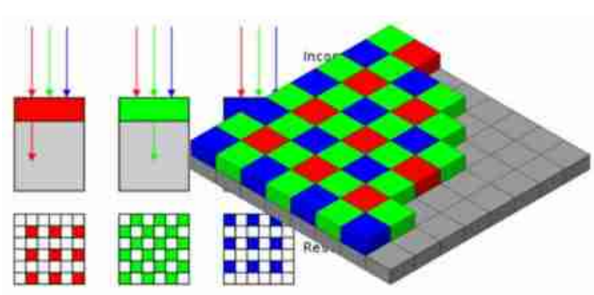


FIGURE 2.3.3: Bayer pattern CMOS sensor

2.3.2 Resolution

The resolution of both analog and digital camera systems is determined with a Modulation- Transfer-Function (MTF). The MTF describes the ratio of the contrast in a scene object to the contrast in the image object for a specific frequency (f). (Stump, 2021, p. 114).

$$(\ ) = \frac{(\ )}{(\ )} \qquad (1)$$

It is measured filming a pattern of alternating black and white bars with increasingly higher frequency. Due to the imperfectness of any visual system, it being a sensor, film, or the human eye, the contrast rendered in the image will reduce the higher the frequency in the object filmed. When the limit of the resolution of a system is reached, the lines will blur unidentifiably and be rendered as homogenous gray (Simon, p., 2019, p. 73). This is called the cut-off frequency. Mathematically, this is a modulation(m) of 0, hence no contrast of the scene is being rendered in the image.

Before the light of a scene is rendered by a recording medium however, it passes the lens to be projected on the image plane. In the process, the aperture and multiple layers of glass that make up the inside of the lens diffract, reflect, and bend the light passing through. It therefore reduces the contrast and has, just like any other component in the optical chain, an MTF that must be multiplied with the MTF of other

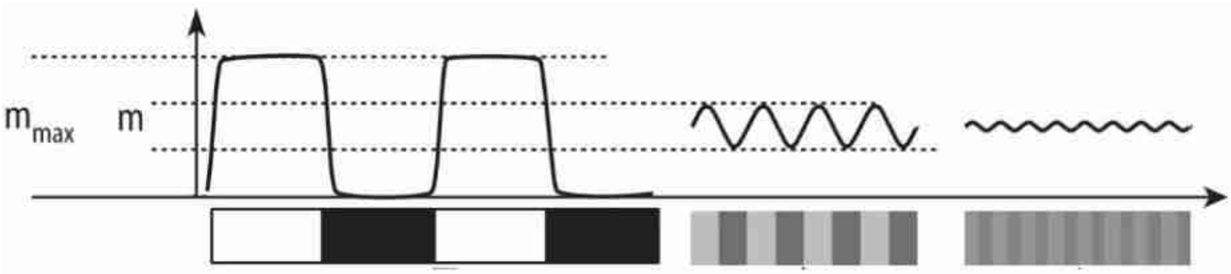


FIGURE 2.3.4: Measuring the MTF

components like a projector to get the OTF (Optical-Transfer- Function) that determines the resolution of the entire visual system (Stump, 2021, p. 112, 116). Since every lens distorts the image across the image plane, wide angle lenses more so than tele lenses, the MTF varies across the image plane and reduces along the outer parts of the image where the distortion is increased (Sturgeon, D. L., 1967, p. 347- 348).

The practically largest impact on the MTF however, is the degree of defocus. Physically, there is only a singular, infinitely shallow plane in space from where the beams of light are exactly focused on the image plane. The further away the object is from this focal plane, the lower the resolution and the lower the MTF. Practically, a small degree of defocus is tolerated. This is called the depth of field. The shorter the lens and the smaller the aperture, the deeper the perceived depth of field and vice versa. Hence, for a long lens and an open aperture, the MTF drops sooner when an object is moved away from the focal plane. An exemplary through focus MTF graph for a given frequency can be seen in figure 2.3.6.

For any filmstock, the resolution / MTF depends on the size of the grain relative to the size of the image plane. The larger the film and the lower the speed, the higher the resolution. Figure 2.3.7 shows the MTF of the emulsion layers of Kodak Vision3 250d. The x-axis refers to the number of cycles or sine waves (pairs of black and white bars) that can be resolved. The y-axis shows the sharpness the lines are separated with. Since the points of sampling, the grain, is distributed stochastically, the resolution is the same in any direction (Kiening, 2008, p. 7).

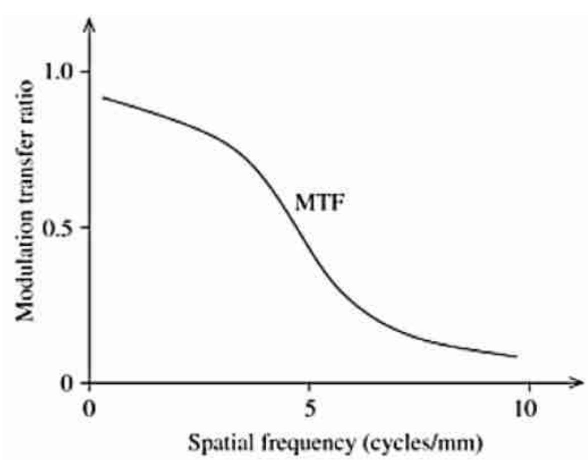


FIGURE 2.3.5: exemplary MTF graph

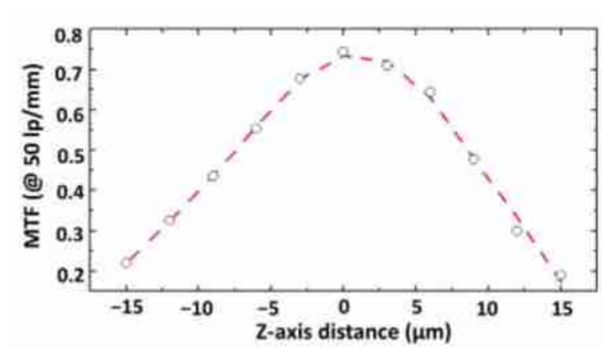


FIGURE 2.3.6: exemplary through focus MTF

Since film doesn't samples colors side by side but in depth, the overlaying emulsion layers are never physically focused at the same time. The image is sharply projected on one emulsion layer with the other two rendering the image slightly out of focus. This is why film is often said to have a soft characteristic.

Similar to the grain on film, the resolution of a digital CMOS sensor depends on the number and density of the photosites. Yet, since the photosites are distributed in a periodic grid structure, the resolution for high frequencies crossing the image diagonally is lower than for horizontal and vertical (Kiening, 2008, p. 7). The resulting periodic sample frequency also makes digital sensors prone to produce aliasing effects when filming high frequency patterns.

In mathematical terms, according to the Nyquist theorem, the sampling rate (in this case the frequency of the sensor grid) must exceed the frequency of a sampled signal (the pattern filmed) by at least the factor 2 to reproduce the signal accurately.

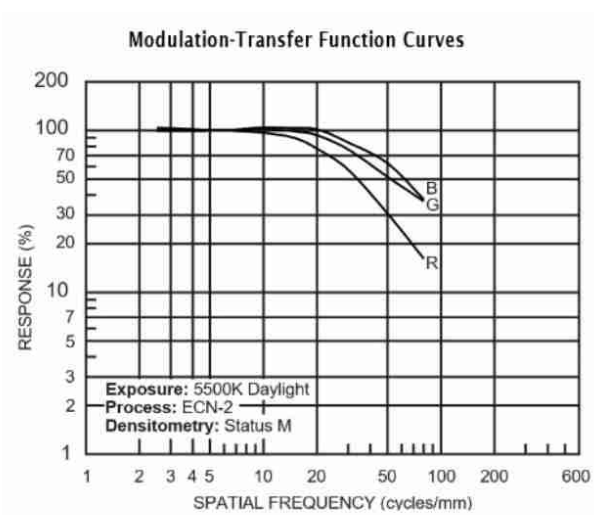


FIGURE 2.3.7: MTF of Kodak Vision3 250d

$$> 2 \qquad (3)$$

In the case of insufficient sampling frequency, an image artifact of lines in various shapes (often in the primary colors of the mosaic pattern in front of the sensels) crossing the image occurs. When shooting with a sensor of 1920 x 1080 sensels, e.g., the highest frequency that can be rendered accurately would be 960 horizontal sinus cycles or 540 vertical sin cycles (one cycle being a pair of one white and one black bar in the test pattern).

To reduce this type of aliasing, the OLPF in front of the sensor diffuses the light passing the lens and spreads it onto several photosites. It thereby aims to cut off any critical frequencies above the Nyquist limit (Stump, 2021, p. 115- 118). Manufacturers aim to design the OLPF to prevent aliasing as much as possible without compromising the MTF to much (Stump, 2021, p. 30). Practically, the OLPF strongly attenuates system response at high frequencies but does not fully eliminate response for frequencies above the Nyquist limit (Schmidt, 2013, p. 77) (De Waal, A., 2012, p. 77), which is why moiré artifacts still occur. Exemplary resulting MTF graphs of a digital CMOS camera are visualized in figure 2.3.9.

FIGURE 2.3.8: aliasing of a digital camera filming a fine line pattern

It should be noted that manufacturers often promote their cameras to have x amount of resolution, referring to the amount of sensels in the sensor, however, due to the Nyquist limit and the OLPF aswell as the de- mosaicking algorithm, the true resolution is only about half of that since not every sensel represents one pixel in the digital image. Even though the output file of the camera might be resized to x-k resolution, the resolution at which the camera can capture detail of a scene is practically always lower (Stump, 2021, p. 34, p. 123).

2.3.3 Colors, Contrast and Dynamic Range

For the sake of this thesis, I will compare KODAK Vision3 250d, scanned with an ARRISCAN in DPX LOG, with an ARRI Amira shooting in prores 4:4:4, log C and AWG3, since these recording mediums are well suited for the purpose of this study as will be explained in the following chapters.

With modern postproduction pipelines and mostly digital delivery, both analog and digital footage undergo the same digital pipeline. Before going into further detail on the mediums' recoding characteristics, I will briefly explain how colors are encoded in the digital realm.

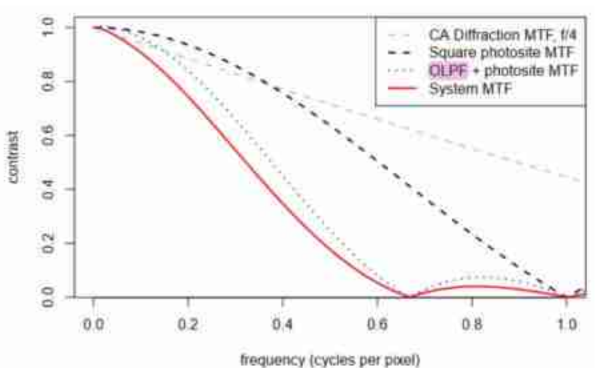


FIGURE 2.3.9: MTF of a CMOS camera

Both natively digital footage and digitized analog footage capture image information as numeric code value. Display devices such as projectors and LCD or OLED monitors, mix red, green and blue light additively to produce a spectrum of colors. In each of these devices, the input digital code values control the intensities of the display primaries (Giorgianni & Madden, 2009, p. 36). However, due to differing device technologies such as the light sources used for projection, the projection capabilities, called the gamut, can vary significantly. To ensure accurate color display and compatibility between devices, standards for the encoding and interpretation of the digital values have been established, several of such color spaces can be seen in figure 2.3.10. The corners of the shapes represent fully saturated primaries and define the boundaries of the color space (Stump, 2021, p. 292). Traditionally, those color spaces were bound to the projection capabilities of designated display devices (this is called "output-referred"). While Rec. 709 is the standard for HD video, DCI-P3 is the standard for cinema projection, to give a few examples. When having a digital image projected, it should first be converted into a color space that fits the gamut of the display device. This conversion happens according to a defined color correction matrix that mathematically shifts the color values, so they land within the boundaries of the destination color space. However, converting from one color space to a smaller one comes with a loss in color information (Stump, 2021, p. 60).

The increasing capability of display devices and the introduction of the ACES color space, which defines boundaries even outside the human visible spectrum, allows scene-referred color space encoding moving forward. Recording in ACES gives the option to convert into any color space and ensuring future proof compatibility with any device and any display capabilities (Stump, 2021, p. 61).

This results in the colors of a captured scene looking different on any device, depending on the device gamut and the color space encoding that should therefore be chosen. Furthermore, the look of an image can be changed to a great extend in color grading. For this reason, high-end recording mediums don't aim to deliver a final look but rather preserve maximum image information and fidelity to provide flexibility in post-production processes for color space conversion, VFX work and color grading. To suit this requirement, both digital cinema-cameras aswell as the latest film stocks record "flat" images, meaning images with little contrast and low saturation to give the freedom to manipulate these values in post. Therefore, the differing recording characteristics of the two mediums such as dynamic range, spectral responsivity and densitometric curves still play a roll. Comparing the visual characteristics of film and digital therefore means comparing the colors the mediums preserve for digital postproduction.

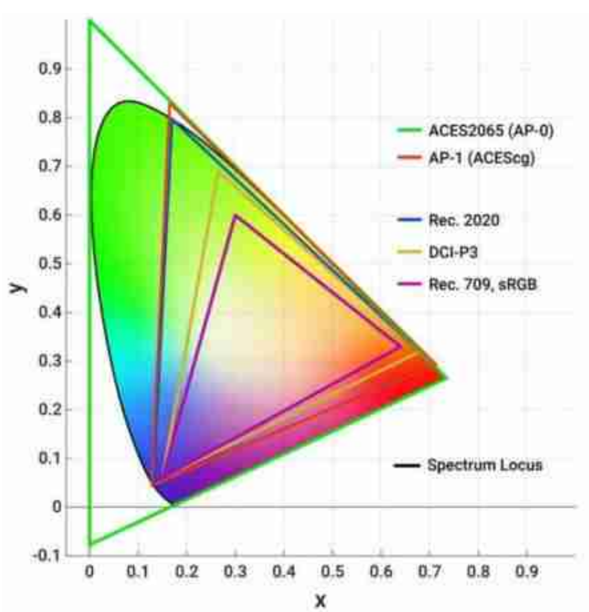


FIGURE 2.3.10: Color Space comparison

Kodak vision3 250d is a filmstock that is balanced to a whitepoint of 5500 Kelvin, thus rendering daylight as neutral or white, and has a speed of 250 ISO. It has around 14 stops of dynamic range. The term dynamic range refers to the range between the brightest and the lowest exposure at which the medium renders image information (Stump, 2021, p. 39). Figure 2.3.11 below shows the spectral response of the emulsion layers. As explained above, in the processing of negative film, the layers form the respective complementary colors of the primary colors they absorb, hence the yellow forming layer is primarily sensitive for wavelengths between 350nm and 450nm.

However, the reaction to exposure in the range of wavelengths these layers are sensitized to isn't linear. In figure 2.3.12, the densitometric curves of the filmstock can be seen. It shows the relation of the logarithmic exposure given in camera stops and the optical density meaning the level of blackening in the respective emulsion layers.

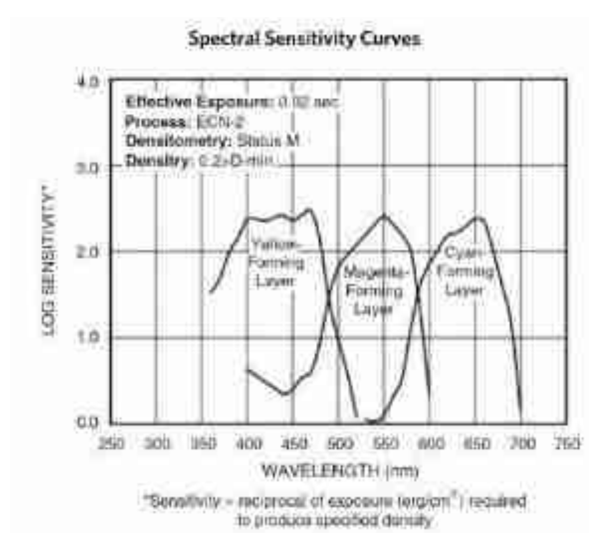


FIGURE 2.3.11: Spectral Sensitivity Curves of Negative Film.

The curves for blue and green are offset vertically from red because they contain more dye to make up for the orange tinted film base (Kennel, 1993, p. 3). The left part of the graph (the toe) and the right part (the shoulder) are curved with the middle part at medium exposure responding linear. This S-curve softens highlights and shadows and makes them “roll-off” (Schmidt, 2013, p. 308- 309). Because of the offset densitometric curves, negative film is not RGB balanced, thus not rendering neutral (gray) values when being exposed to equal RGB stimuli (Brendel, 2005), which is an effect that is compensated during printing and scanning (Kennel, 1993, p. 4).

Film has more latitude when being overexposed (around 8 stops) than when being underexposed (around 6 stops) which is why DPs often “expose to the right”, meaning overexpose the image to retain sufficient image information in the shadows (Stump, 2021, p. 19)

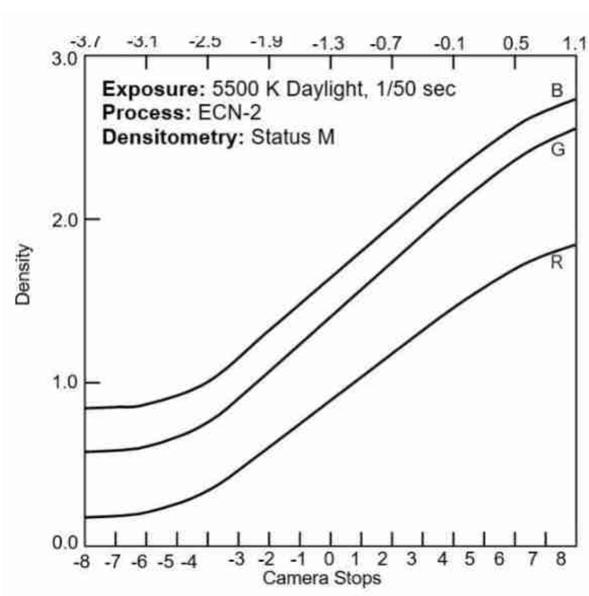


FIGURE 2.3.12: Densitometric Curves of Negative film

The colors on the exposed negative can then be affected by different means of processing. The timing, temperature and chemical components involved also influence the characteristics of the Look. For simplicity, we assume that the negative undergoes regular ECN-2 Processing. It is now digitized (for an explanation of the scanning process see chapter 2.3.4).

As for the ARRI Amira, the spectral responses of the photosites for red, green and blue are as shown in figure 2.3.14 below. The white balance and ISO are adjustable, and the dynamic range is also around 14 stops (ARRI, 2018, p. 3).

When aiming to preserve maximum image information, shooting in Log-C is recommended. The Log- C profile logarithmically encodes the luminance (ARRI, 2018, p. 3), similar to the response of celluloid film. That way, the highlights and shadows in a scene are muted and less likely to clip. The remaining difference to film, however, is the linearity of the response curve over the entire dynamic range without shoulder or toe.

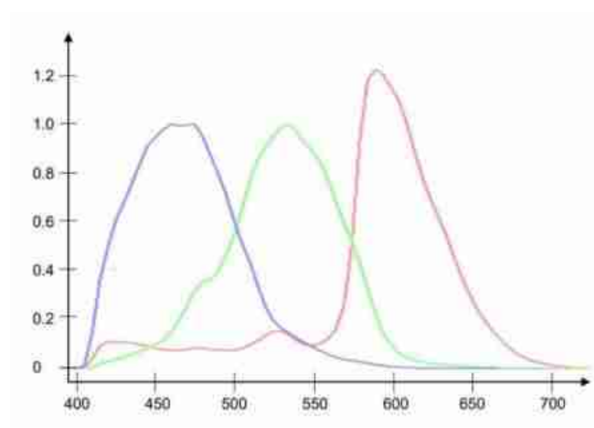


FIGURE 2.3.13: Normalized Spectral response curves of ARRI Amira

Even though the sensitivity curves of the vision3 stock aren't normalized, we can see that the red sensitive emulsion layer peaks at 650nm, whereas the red sensitive photosite peaks at 600nm, e.g. In essence, the color filtered photosites and the sensitized emulsion layers respond to other ranges of wavelengths and to a different extend in relation to the exposure. However, to quantify this contrast and give general answers, numerous tests of varying lighting situations, color palettes, exposures and so on would have to be shot side by side and analyzed. Without grand scale tests as such, the difference in behavior can only really be pinpointed for one specific set of tested conditions at a time since every variable in the captured scene or the imaging chain has an influence on the final color. This also only ever quantifies the color responses of the two recording mediums. To compare the preserved color of film and sensor in the digital realm, the way the film scanner translates the color of the negative into digital values must be considered.

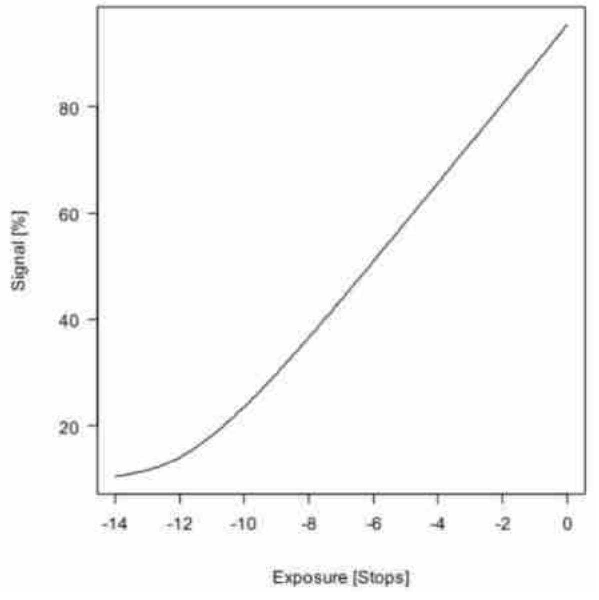


FIGURE 2.3.14: ARRI Amira Log C Curve

2.3.4 Scanners

There is a variety of film scanners utilizing different technologies. Judging from KODAKs Lab Directory Website, the scanners of ARRI, DFT and LASERGRAFICS pose the industry standard for motion picture scanning (KODAK, n.D.). Each of which makes use of a digital sensor as a pickup device, following a similar principle as a projector.

In each of these scanners, the film is transported over an LED lightsource that illuminates the negative. The film stops for every frame while a digital image is taken from above (Schmidt, 2013, p. 344). Cheaper scanners such as the LASERGRAFICS' ScanStation or Archivist pick up the negative with a CMOS sensor like it can be found in a digital camera with an OLPF and a bayer pattern with the sacrifices in resolution mentioned above.

In the ARRISCAN, or the LASERGRAFICS Director, on the other hand, the film is transported over a multicolor LED light source flashing each frame red, green, and blue one after another, while three digital images are taken from above. The pickup device is a filter less, monochrome CMOS sensor. An additional infra-red illuminated image is taken to detect and reduce scratches on the negative. The three images in the primary colors are then mixed additively to produce a color image. The ARRISCAN can be run in 3k or 6k resolution, however, since there is no bayer pattern in front of the CMOS sensor but singular 3k/6k images taken for every primary color, it has true 3k/6k resolution since every pixel contains RGB information with no interpolation needed (Schmidt, 2013, p. 345). The files of a 6k scan are output down sampled to 4k respectively.

The DataCine Spirit 2k and 4k and the Scanity HDR from DFT don't flash the negative with red, green and blue, however they both use 3 CCD sensor chips and a beam splitter, dividing one white illuminated frame into separate images for RGB which also result in 2k / 4k true resolution (DFT, n. D.) (DFT, n. D.).

The output files of these scanners can be chosen between several formats such as DPX, ADX, TIFF and many more with adjustable resolution, bit depth and gamma curve (LASERGRAFICS, n. D.). Since all these scanners involve several optical components such as a lens and the imaging sensor, some also filters, they have an MTF that further reduces the contrast rendered on the negative. The nature of digital sampling also implies the risk for aliasing artifacts, when a high frequency pattern, exceeding Nyquist limit of the pickup device, is visibly rendered on the negative (Kiening, 2008, p. 12- 13). The lack of an OLPF in the ARRISCAN and LASERGRAFICS products does increase the chances for aliasing in the digitized image. However, since they both provide high resolution scanning settings up to 6k or even 13.5k, this can largely be prevented because frequencies above Nyquist limit for such sampling frequencies are rarely visibly rendered in the film negative (Kiening, 2008, p. 15) (Schmidt, 2013, p. 345). This is because frequencies that high are often cut off according to the MTF of the imaging chain prior to the scanning step.

As for color rendition, the device architecture and software dictate the way the inverted color of the negative is preserved in the output image data. Scan manufacturers aim to preserve a look from the negative that resembles the look of a film print (Brendel, 2005). Specifically, the illuminants are "designed so that the effective spectral response of the scanner matches that of print film" (Kennel, 1993, p. 9) for the given filmstock that is being digitized. Practically, this means the scanner tries to emulate how a print film "sees" the negative. However, since this depends on the print film stock and the printer lights used in the printing device, this can't be exactly defined (Brendel, 2005).

Until further examination, I will use the experience of industry professionals such as Image Engineers and Colorists as a basis. One major difference between film and digital seems to be the rendition of skin tones. According to Andy Minuth and Daniele Siragusano, Colorist, and Image Engineer at FilmLight, film generally compresses skin colors to a certain extent, rendering skin tones with less variation in the green- magenta axes than digital, while retaining subtle, natural color variation (Siragusano, 2022). Florian 'Utsi' Martin, senior colorist at ARRI comes to a similar conclusion and explains, "On most digital cameras, two Caucasian skin tones are often rendered further apart from each other than what we are used to seeing on images shot on negative stock" (2016). However, it is difficult to pinpoint how much of this "film look" in terms of color rendition comes from the negative, how much comes from the print and to what extend this is emulated by the scanner.

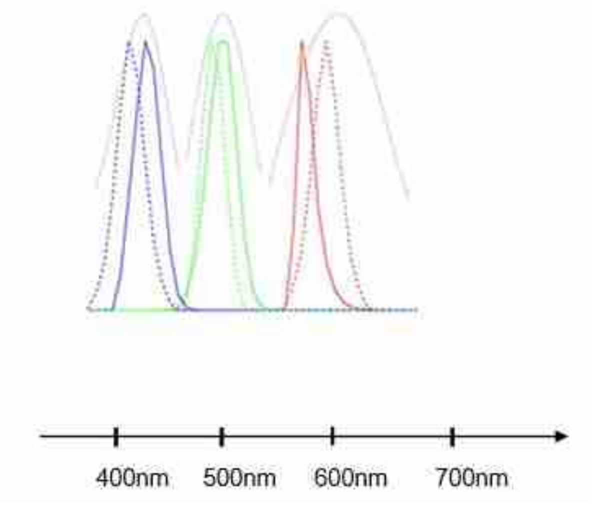


FIGURE 2.3.15: Spectral responses of the negative and the scanner according to SMPTE

The Society of Motion Picture and Television Engineers (SMPTE) released a set of proposed spectral response curves for motion picture film scanners to emulate an average print film look in the digitized negative (Brendel, 2005). Figure 2.3.16 below shows the relation of the proposed spectral response curves by SMPTE (dashed lines) to the spectral response curves of the negative (gray lines).

As can be seen, the dashed curves of the red and green layer don't match the response curves of the negative, hence a shift in color can be expected. A scanner that matches these response curves and successfully emulates "average" characteristics of print film, would result in surfaces such as skin tones which lie in between red and green to potentially be compressed and rendered with less variance. This is not guaranteed however, since scan manufacturers also have to take other parameters like dynamic range and signal to noise ratio into consideration when designing a scanner which is why this behavior will differ. This makes in-depth analysis of this behavior complex beyond scope of this thesis.

2.3.5 Shutter

In common film cameras, the shutter is a half-circle (when shooting at 180° shutter) mirror-dish that rotates in front of the image plane once for every frame captured. Whenever the shutter is positioned to the side, the light that passes the lens directly hits the film and exposes it. When the shutter covers the film, instead of exposing the film, the image is reflected into the viewfinder. This has the effect that the viewfinder doesn't show a continues image but flickers heavily and only ever displays the moment the film is not exposed, thus an image that is not being captured in between images that are (Schmidt, 2013, p. 423). This is of importance when shooting in an LED- volume which will be explained in the following chapters.

High end digital cinema cameras are mirrorless and therefore don't have mechanical shutter and viewfinder but electronic controls of the pulse at which the image is sampled and transmitted, with the sensor being exposed at all times. A rolling shutter reads out the photosites line by line whereas a global shutter reads the entire image at once (Stump, 2021, p. 36- 37). Both practically allow for a continuous image to be transmitted to the viewfinder and other monitors on set in real-time.

2.3.6 Differences in workflow

Because of their differing properties, the two mediums are chosen for different tasks. Due to films lower speed, e.g., digital cameras are often technically beneficial when shooting night exteriors since less light is needed (Kenneally, 2012, 00:57:38-00:57:54). Film on the other hand is to this day a creative choice considered when going for a specific look (Kenneally, 2012, 01:27:23- 01:27:44).

On set, shooting digitally versus shooting on film makes a crucial difference in the workflow, one of them being the monitoring on set. When shooting on film, the image captured can't directly be displayed. The only reference is the viewfinder of the camera,

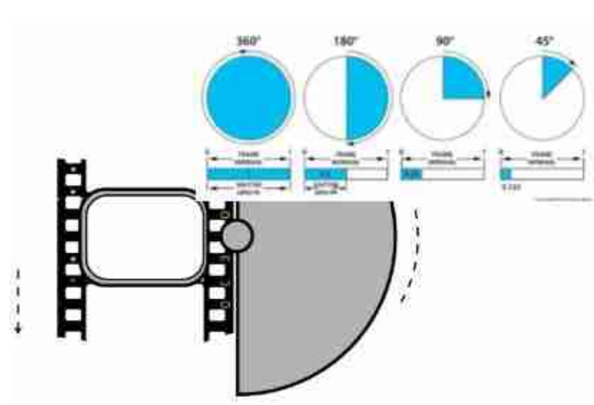


FIGURE 2.3.16: Mechanism of an analog Shutter

and that also has limitations. In Addition to the flickering, the image in the viewfinder doesn't give any reference on how the filmstock used renders the light concerning exposure, colors, and contrast. A lot of experience is required to know what the output image will look like. The only way other than the viewfinder that crewmembers can see the camera image, is via a small digital camera on the body of the film camera that captures the image on the focusing screen. Since at the time film cameras were built digital cameras weren't developed nearly as far as they are today and the camera had to be small to fit, it's resolution and color quality are quite poor. As it films the image that is reflected by the shutter, it flickers just like the image in the viewfinder.

When shooting digitally on the other hand, the image is captured as a numeric signal that can be transmitted and manipulated in real time. When recording in a flat format like ARRIraw or log C, a LUT is often applied to the image to give an impression what the final image will look like (ARRI, 2018, p. 5-6). This allows the production crew to see and judge their work reliably in the final frame and react on set. A Digital Image Technician (DIT) can provide additional on set grading and overlook the image in relation to exposure and technical errors like image artifacts.

Furthermore, the limitation of the film magazine on analog cameras is almost trivial since the digital equivalent, memory cards, can capture a lot more footage. This can introduce an entirely new workflow on set with the camera running non-stop to capture every bit of an actors' performance. Even though this can provide more freedom for actors and directors, it can slow down the editing because of the amount of footage captured.

Since modern delivery is mostly on streaming services or in cinemas via a DCP (Digital Cinema Package), analog footage must be scanned and goes through the same pipeline of digital editing, visual effects, and color grading just like any natively digital footage, thus simply being a detour to the digital end product from a technical standpoint. On digital cameras on the other hand, the footage can be handled right away which reduces costs and minimizes the risk of losing the footage due to accidents as it can be copied onto multiple memory cards immediately by the data wrangler. This also means that the postproduction can begin as early as the footage is wrangled which sometimes means an editing assistant starts rough editing during principal photography.

2.4 Conventional Method: Digital LED-VP

2.4.1 Setting up a Volume shoot

2.4.2.1 Camera tracking and synchronization

When preparing to shoot in an LED-volume, the synergy of several hardware and software components must be ensured to make the ICVFX work. One aspect is the tracking of the camera in combination with Unreal Engine, to ensure accurate parallax. Common systems used for camera tracking in virtual production include MoSys, Ncam, OptiTrack, StYpe, and Vicon (Kadner, 2021, p. 25). The tracking systems consist of multiple sensors that track the movement of a specific tracking object in the studio space, similar to the method used for human motion capture. Since these systems don't directly communicate with the camera itself but only as a closed loop between tracker and sensors, they are combinable with any camera. The recorded movement of the physical camera can then be translated into movement of the virtual camera in the virtual environment in real time (Kadner, 2021, p. 25).

According to the position and the angle of the tracker, thus the camera, the perspective on the LED-wall shifts. In order to safe computing power, the displayed image on the wall is separated into what is called the inner and the outer frustum. The inner frustum covers the field of view of the camera and is a high resolution, real time render of the virtual background in the correct perspective. Since a longer focal length results in a smaller field of view and vice versa, the focal length in use must be communicated to the wall operators at the Brainbar in order to account for its specifics. The outer frustum does not account for the movement of the camera and is a low-resolution render of a single perspective of the environment. This is still enough to cast ambient light in the scene and believable reflections (Kadner, 2021, p. 61- 62).

As for synchronization, the primary PC and the cluster PCs rendering the image on the LED-wall in real-time must have the content ready simultaneously.

FIGURE 2.4.1: The inner and the outer frustum

In the case of Unreal Engine, this is realized with the nDisplay technology (Dalkian, 2019, p. 3).

On a hardware level, the display swap, which is the switch between the current image to the next one on the wall must be in rhythm with the shutter of the camera, thus the moment the image is captured, to prevent tearing artifacts in the wall (Sony, 2022, p. 17). This is achieved via a sync-generator that sends a synchronization pulse to devices such as the camera, monitors and other displays so they all display and capture the next frame at precisely the same time. This can be realized through

various ways like a timecode generator, however, In the film and TV industry, genlock is commonly used. In the application of real- time rendering in the volume, "...specialized hardware sync cards and compatible ... graphics cards" such as the NVIDIA Quadro components are required to synchronize the output of the graphic cards and "... lock it to the received timing signal or pulse" (Dalkian, 2019, p. 9). This way, the rendered frames are displayed simultaneously.

2.4.2.2 Color calibration

Since every camera system has specific properties for color rendition due to its sensor architecture and the color science behind it, each camera model will render the colors emitted by the LED-wall differently. This principle is no different than when shooting on location. However, LED-walls work in specific color spaces, defined by the primaries, hence, they have defined spectra they emit when projecting a certain color value they receive from Unreal. This color space does not implicitly match the native recording color space of the camera in use. In order to have a fully saturated red in the virtual scene look like a fully saturated red on camera, e.g., the LED-wall needs to be calibrated so the emitted spectra result in the desired color in the camera.

This calibration can be implemented with OCIO (Open-Color-IO), which is an open-source color pipeline by Sony Picture Imageworks. OCIO communicates with several programs such as Houdini, After Effects, Nuke and Unreal Engine, to ensure consistent color transformation and color rendition between these programs (Selan, 2012, p. 43). An OCIO Configuration file contains so called Transformations like LUTs and matrices. Several of which are set up to shift the color values for optimal color reproduction, the most important one being a 3x3 color correction matrix (in the case of LED-wall virtual production) (Payne & Giardiello, 2022). It is calculated by projecting primary color patches on the wall and recording how the camera "perceives" those. These primary values define a new target color space, that is then compared with the color space of the LED-wall. The color correction matrix is generated "to map the extracted color space to the intended target." (Payne & Giardiello, 2022).

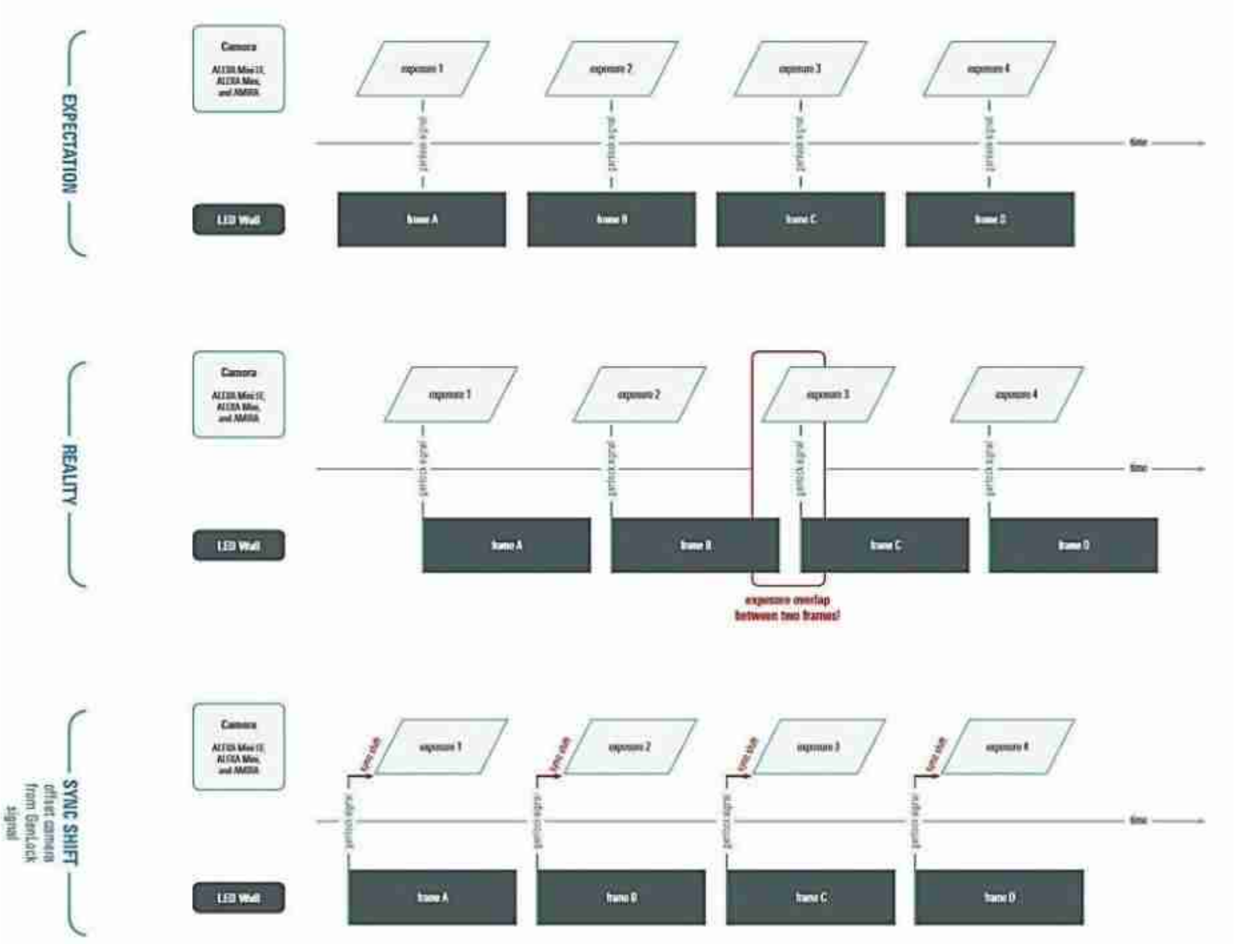


FIGURE 2.4.2: Camera to LED-wall synchronization

This matrix, in combination with a white shift and a gamma compression work together to practically shift every output color value from Unreal so the wall emits a spectrum that results in the correct color in camera. Since every color projected on the wall is a linear combination of the primaries, matching the values for RGB will also match all other colors, Chloe LeGendre, research scientist at Netflix, (2022) explains. This way, the colors in the virtual scene can be adjusted with an accurate representation in the final image.

2.4.2 Limitations of the Volume

2.4.3.1 Focusing the LED-wall

Especially regarding the cinematography, there are several things to consider to not run into technical difficulties and avoid image characteristics that take away from the sense of reality of the scene, some of which can be prevented by keeping the wall out of focus.

One of these characteristics is unrealistic depth of field. Since the virtual content in Unreal has no information about the depth of field or the focal plane of the camera, it does not account for it. Hence, the entirety of the virtual set extension is rendered in focus. The bokeh in the background is identical for every layer of objects in the virtual set extension because it's all projected on the same image plane and therefore has the same distance to the camera, unlike when shooting on location. When kept out of focus, this isn't noticeable for the most part because it all blurs and the attention of the audience will be on the focused subject instead of the background. Once the background is in focus however, the lack of depth and focus falloff becomes apparent, and the image tends to look flat. Furthermore, when focusing the LED-wall, double images due to the wall and the camera being off sync will be more noticeable.

Since LED- volumes natively provide a high frequency, periodic grid pattern due to the pixel structure of the LED-walls, this shooting environment heavily provokes aliasing. In the instance of two periodic patterns (the sensor pattern and the pixel pattern) interfering, the occurring aliasing image artifact is called moiré.

Even though the sampling frequency of any given camera (depending on the photosites) and the frequency of the pattern filmed (in this case the pixelpitch of the LED-wall) physically stay the same, the relative ratio of the frequencies change, depending on the distance and the angle of the camera to the LED-wall aswell as the focal length attached to the camera.

This makes moiré difficult to predict. Filmmakers often keep the background out of focus as much as possible, making use of the low pass filter effect, that blurs the high frequency grid of pixels and the space between them. This is typically achieved by keeping the focal plane off the wall, opening the aperture, and positioning the subject and the camera as far away from the LED-wall as the studio space allows (Kadner, 2019, p. 40). The latter increases the frequency of the pattern filmed relative to the pattern of the sensor since a larger portion of the wall fits the viewing angle of the camera, and therefore risks the chance to have the frequency of the wall exceed

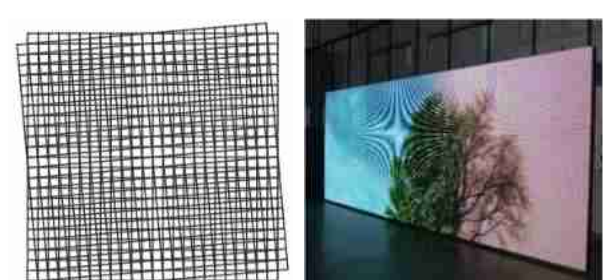


FIGURE 2.4.3: Moiré in on an LED-wall

half the sampling frequency, however, it helps to keep the wall further away from the focal plane and also reduces the sensors' ability to render contrast according to the MTF.

2.4.3.2 Lighting

When projecting a virtual scene onto an LED-wall, the wall will act as an ambient light source for the physical set in the foreground that implicitly matches the background. LED-Volumes are therefore often promoted to provide so called Image-Based-Lighting, meaning that the light the LED-walls cast on the props and actors matches the light of the virtual location as if it were shot on location, thus behaving perfectly natural and making further lighting obsolete. However, there are several differences to consider between ambient light in a volume and on location. One of them being the color.

RGB-LED panels used in volume setups mix red, green and blue light additively to produce a spectrum of colors, hence, the spectral characteristics differ to ambient daylight or light created by high-end filmlights like Tungsten, HMIs or high-quality LED-Lights. Whereas the latter have an even spectral power distribution, the panels have narrow bands in the blue, red and green wavelengths and gaps in between.

Figures 2.4.5 and 2.4.6 below show a comparison of the spectra, and resulting reflectance on skin tones, of such a high-end film-light, the ARRI ORBITER, and a common LED-panel used in LED-VP, emulating white light. While the LED-panel manages to produce the same color temperature at the source (they are metamers), the color reflected by an object might not match. This is called metameric failure, or a lack of metamerism. This is why filmmakers often work with additional, broad spectrum, light sources to close the gaps in the spectrum when emulating natural daylight. When comparing a broad spectrum light source to an RGB LED-panel, the LED-panel will perform better at replicating accurate reflectance for lighting scenarios that are more saturated since they have a narrower power distribution by nature.

As this spectral-power-distribution graph demonstrates, the light of the LED-wall is composed of red, green and blue narrow-band spikes, while the cinema-fixture lighting has a more evenly distributed broad spectrum. The line at the back of the graph illustrates the spectral distribution of natural daylight at the same Kelvin temperature as the LEDs.

For human perception, such color shifts as shown in the figure above are especially noticeable in human skin tones (Schmidt, 2013, p. 72). Skin tones also lie within the range of wavelengths perceived as orange, hence the gap between green and red where almost

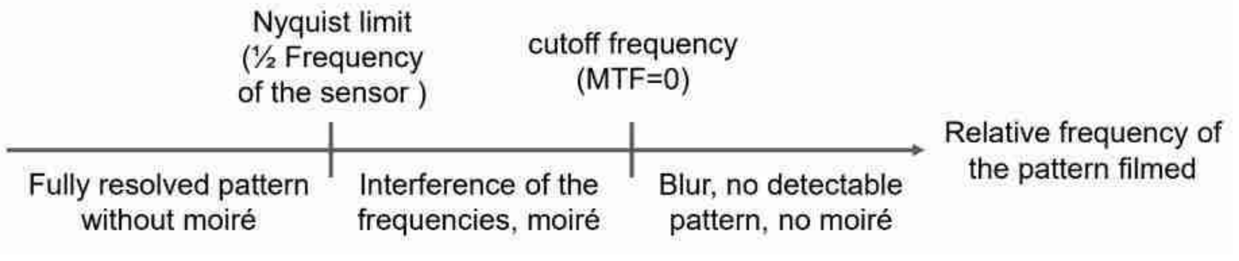


FIGURE 2.4.4: The occurrence of moiré

no power is emitted by the LED-panel. Under lighting conditions as shown above, skin tones will therefore typically either drift towards green or red, depending on the spectral power distribution of the source. Still, this only accounts for the objective wavelengths reflected by an object being hit by a specific spectrum of light. Depending on the sensitivity for wavelengths of the cones, sensels or emulsion layers, the perception will differ. The concept of observer metamerism also applies for different camera models or recording mediums.

Another difference to ambient light on location is the light fall-off. Light fall-off can be calculated with the inverse square law

$$= 1/ \ {}^{2} \qquad (4)$$

with d being the distance to the source. This means that the amount of light devides by four when the distance from the source doubles. Having an overcast sky projected by the LED wall, e.g., the ambient light created by it will fall off drastically in the set, whereas real overcast daylight won't fall of

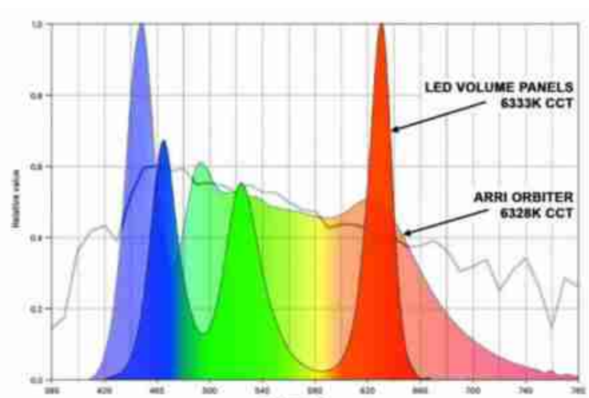


FIGURE 2.4.5: Spectral power distribution of ARRI Orbiter and RGB LED-panel

noticeably within a real location. Light quality is also limited to soft light, since the large LED-panels can't produce focused, parallel light beams. DPs often work with additional, cinema light sources to counter these effects (Kadner, 2019, p. 75).

2.4.3 Workflow in the volume

In general, shooting in an LED-volume opposed to shooting on location or another type of studio like a green screen stage will change the order of post and preproduction. Digital worlds and effects that are otherwise created after principal photography and added into the (partially) edited footage must be prepared in advance to be projected live on set (Kadner, 2019, p. 7).

This changes the workflow on set, the communication and the responsibilities of the departments involved. The Brainbar is typically a central point of communication since the content on the wall ties together the responsibilities of Director, DP, Lighting department and the Production design. In interest of the DP, color, contrast, and luminance of the scene on the wall, hence also the ambient light casted by the wall, can be adjusted and the lighting can be set up accordingly or vice versa (Kadner, 2019, p. 38-39). Together with production design, the Unreal artists work to create a believable transition between the real set and the virtual set extension, place or remove objects in the background and match foreground and background colors to tie the scene together.

FIGURE 2.4.6: Metameric Failure in the LED-volume

The fact that all these parameters can be adjusted in real-time and the effect of which monitored in the live camera image makes it an entirely controlled scenario. This ICVFX gives the advantage of seeing what you get on set. Filmmakers often call this “What you see is what you get” (WYSIWYG) (Kadner, 2019, p. 4). The Unreal artists being able to see the exact live image of the camera means they can work self-sufficiently with the different departments, although the DP of course shouldn’t be left out of a discussion concerning the lighting for example. Image artifacts by synchronization or pixel structure can be monitored immediately by the DIT looking for tearing artifacts, double images, or unwanted textures in the background. By preventing such errors on set and creating a realistic look, productions hope to eliminate extensive post-production work (Kadner, 2019, p. 49).

Due to the hardware and software components involved, shooting in a volume generally comes with several technical limitations. For example, most common LED-panels used for LED-VP can only project up to 60 frames per second which makes shooting super slow-motion with 100 fps or higher impossible without having flicker artifacts in the wall. Hence, great care must be taken in preproduction when conceptualizing shots. Ideally, the shots should be talked through with the LED-wall operators and tested in advance. Spontaneous changes on set can lead to unforeseen complications. Even though this can generally be said to be the case, it is especially true when shooting in a volume since the content on the wall might not be ready for what a newly thought up shot would require, whereas a VFX shot in post might allow for such adjustments.

2.5 New Method: Analog LED-VP

2.5.1 Potential advantages

Due to a combination of several parameters such as the behavior of light and depth of field, scenes shot in a volume often tend to look unnatural and synthetic when not done precisely right. This is often called “gamification”. In theory, film with its’ more natural color rendition and its’ organic texture could help minimize this phenomenon.

Specifically, concerning moiré, shooting on film could reduce moiré artifacts and thereby liberate creative choices. Since the grain structure of celluloid film is irregular opposed of the periodic Bayer pattern of the digital sensor, moiré doesn’t occur on the film negative by plainly filming the wall because its sampling frequency is random and different for every frame. This alone does not exclude the possibility for moiré in the final digital image since when the pattern of the wall is visibly rendered on the negative, the digital pickup device of a film scanner like the ARRISCAN provides a second grid pattern that can create moiré through scanning. For better understanding of this relationship, I will give a rough and simplified example, with quotations and references for plausibility of the numbers used.

> we assume a setup with an LED-wall with a pixel pitch of 2.6mm (this is considered one cycle, one bright pixel and dark space next to it) (Kadner, 2021, p. 60), and two cameras, positioned 6,00m away, orthogonal to the LED-wall. One of them being a 35mm 3 perf film camera and the other an ARRI AMIRA shooting super 35 4k UHD. Both have the same 50mm lens attached and keep the focus on the subject in the middle ground.
> The angle of view of the lens is around 40 degrees and tan(20)× 6,0m˜2.2m, hence roughly

4.4m or 4400mm of the LED-wall fit the roughly 24mm wide image plane of both cameras resulting in 1700 line pairs of rows of pixels and space in between them, thus 70 cycles per mm of the image. Due to its visual imperfectness, the lens has an MTF of 0.6 for this given frequency. Due to the lens, the opening of the aperture and the chosen focal point on the actor in the mid ground, the depth of field almost reaches the LED-wall, and the focus through MTF is around 0.8 for the given frequency. The filmstock and the CMOS sensor both have an MTF of 0.3 (see figures 2.3.7 and 2.3.9). The resulting OTF of both visual systems is 0.6 x 0.8 x 0.3 = 0.144, hence, 14% of the object contrast is visibly rendered on both mediums.
Since a low contrast pixel structure is still visible to the digital sensor, the image renders moiré because the 3.2k actual sampling frequency (ARRI, n. D.) does not exceed the sampled frequency of 1.7k line pairs by more than factor 2. The film negative renders a visible grid structure without moiré and is scanned with 6k resolution ARRISCAN. The scanners sampling frequency exceeds the sampled frequency of the LED-wall pattern on the negative by more than factor 2. The digitized footage therefore doesn't render moiré artifacts, but a fully resolved, low contrast pixel grid. However, when downscaling the image to 4k, which softens or blurs the image, the pixel structure of the wall is gone (Kiening, 2008, p. 15) (Schmidt, 2013, p. 345). The result of this comparison is a natively digital image, upscaled to 4k, with moiré and a digitized film image, downscaled to 4k, without moiré.

In this specific scenario, film would pose advantageous over digital, however, every component in the visual chain and adjustments of camera placement all impact the equation, making this case almost impossible to prove. Still, having the additional step of the negative in the optical chain from scene to digital image could help to reduce moiré. Firstly, it is an additional component with visual imperfectness and a resulting MTF that can help bring the system MTF closer towards 0 and therefore prevent the rendition of fine patterns and moiré. Secondly, even if the LED-wall pattern is visibly rendered on the negative, an occurring moiré artifact is not "baked" into the footage, since it can possibly be prevented in postproduction by scanning at higher resolution, thus exceeding the Nyquist limit. If this excludes moiré to a great enough extent, less compromises on lens choice etc. would have to be made and the wall could even be in focus without creating moiré, liberating the camera, and even enabling new shots. For example, having the actor out of focus and reacting to something that is happening on the in-focus wall could create a real sense of the actor standing in the environment and make the scene look more believable.

Since the response curves of celluloid film and digital sensors differ, the way film renders colors and therefore metameric failure also differs. Whereas the emulsion layers of film respond to a broad range of wavelengths, the sensor shows comparatively narrow band response. The narrow band reflections of a surface illuminated by the LED-wall are therefore more likely to fall outside the sensor's response curves than films. Film might therefore render metameric drifts with less apparency and prove to be advantageous. Especially if a scanner successfully emulates the behavior of the print film, and compresses skin tones, this could impact the approach to lighting in the volume with less external light sources needed to achieve natural looking colors, since human perception is especially sensitized to color shifts in skin tones. Image based lighting might therefore be more attainable when shooting on film compared to shooting on a digital camera.

2.5.2 Potential disadvantages

On the other hand, integrating film and an analog camera into an otherwise entirely digital workflow, with not only a digital postproduction pipeline, but also digital on set routines like synchronization and the color calibration with the volume, could come with tremendous technical obstacles.

Shooting on film excludes reliable monitoring which could make monitoring image artifacts a lot harder. The only way to judge image artifacts and metamerism when shooting on film would be the viewfinder and the human eye. Of course, judging the image via these two primary tools has been the established film workflow for decades. When working in a volume however, this could seriously hinder creative workflows since a reliable live camera image is often the base for communication.

Even though moiré could be less problematic, there is no way to monitor it on set because it only occurs during scanning and not recording. Even looking for a resolved pixel grid which risks moiré in the scans would not be possible since neither the human eye nor the video playback represents the films resolution.

Monitoring other artifacts like tearing artifacts or double images caused by the wall and the camera not running at the same pulse, could also be harder to judge because of the nature of the analog shutter. When only seeing the off-phase (the moment the image is not captured), double images should be noticeable in the viewfinder to prevent them in the on-phase. This could be quite difficult to monitor with only a flickering image to judge from.

Metameric failure, even though potentially less apparent, or at least rendered differently on film, would be impossible to accurately judge since none of the available monitoring tools accounts for the color and contrast rendition of the film. There would be no way to judge if additional, broad-spectrum light is needed to ensure natural looking skin tones on the film.

Technical and creative aspects such as monitoring tearing artifacts or the visual transition between foreground and background are typically done via the live camera image. The DP now having have the most accurate image to look at, that being the viewfinder, would probably become more of a center point. One primary argument of the volume (WYSIWYG) could be lost since you're standing on set guessing, with creative work being hindered by technical uncertainty and hick ups.

3. METHODOLOGY

3.1 Preproduction

3.1.1 Conceptualization

When specifically testing for moiré or color rendition, numerous scenarios with differing camera models, film stocks, camera positions, lenses, apertures, focal lengths, scanners, lighting situations, LED-walls and so on would need to be shot side by side and compared to give definitive answers how the two mediums render the scene different from one another. While results as such would certainly be interesting, they would barely serve the practical purpose of giving productions a guideline on how to shoot in a volume. Moreover, investigating upon moiré, colors and metamerism in such depth in laboratory-like conditions would have gone beyond the scope of this thesis.

Instead, the tests were done based on a real production with industry standard conditions. This way, the practical relevance of the advantages and challenges could be investigated. The entire production was shot in both digital and analog to be able to compare both version regarding moiré, colors, and the integration of the analog camera in the volume- workflow. The digital camera also served as a viewfinder.

The fact that we were going to be shooting in the LED- volume made us decide for a rooftop which only comes with complications such as shooting permits, safety hazards and logistical problems when shooting on location, which are all eliminated when shooting on stage instead. We set the time of the story to night-time and dawn, since this typically poses challenges due to exposure when shooting on film which were hoped to be eliminated due to the control of the luminance the volume provides. We conceptualized a shotlist that would fit the creative concept and provoke meaningful results for the technical research simultaneously. We ended up with five shots in Total: Two to investigate on moiré, one of which specifically focusing the wall (2.3, figure III) and the other one on a wide-angle lens with the camera being positioned close to the wall thus implicitly having the wall in focus (2.5, figure V) and three that included the night sky in a large portion of the frame (2.1, 2.2, 2.4, figures I, II and IV). We communicated this shotlist with the unreal artist so she could start building the environment and with the wall operators so they could tell us about potential technical difficulties with the shots.

3.1.2 Testing stage

In the testing stage previous to the actual shoot, we shot 35mm Kodak Vision 3 250d vs Blackmagic URSA 4.6k in HYPERBOWLs LED-volume side by side and tried to provoke moiré by going close to the wall and putting it in focus. We used an Aputure 300d with a softbox as additional lighting equipment providing an edge light, a key light via a white bounce board and a fill light only being illuminated by the volume.

We had the footage processed and scanned at SILBERSALZ LAB in Stuttgart with a Cintel Scanner in 4k resolution. The result was a fully resolved pixel pattern in the digital footage without moiré, a resolved pixel pattern in the negative without moiré and moiré in the 4k Cintel scan. Since both the Blackmagic URSA and the Cintel Scan work with Bayer-Patterns, their resolution is comparable. We concluded that for our specific testing conditions, the difference between 4k and 4.6k seemed to be the threshold for moiré. The 4.6k Ursa sensor provided grid pattern that exceeded double the frequency of the pixel pattern of the LED-Wall while the 4k sensor of the Cintel Scan did not. To prevent moiré, the footage would therefore have to be scanned at a higher resolution.

In DaVinci Resolve, the color space of the ursa footage was transformed into an ARRI color space, to imitate the look the AMIRA would produce. This was then used to compare the footage in terms of colors and contrast to the scanned analog footage. This comparison should have been the base for a LUT loaded into the Amira to give a reference what the scene will look like on film. My goal was to light the scene and adjust the values of the virtual scene to make it look good on film because this would be the prioritized footage for the end product. We did not end up doing this however, due to a shortage of time in preproduction.

To accurately calibrate the LED- wall for the shoot, we also shot primary color patches on the led wall with both the Amira and the 250d filmstock to capture how the mediums render these colors. The analog footage was also ECN-2 processed and scanned with a Cintel scanner at SILBERSALZ LAB and was meant to be the base for a color correction matrix. Figure 3.1.1 below show ARRI Wide gamut 3, the native color space of the HYPERBOWL LED-wall and the color space defined by the primaries perceived from the mediums when filming the color patches on the LED-wall, “noCall”, with the filmstock on the left and the Amira on the right.

For the Amira, the LED- wall could be accurately calibrated. For the filmstock however, it was noticeable that the resulting color space of primaries as perceived by the negative and digitized by the scanner was quite small, with primary values similar to sRGB. Knowing that films color space is typically way larger than that, it concluded that the Cintel scanner had scanned the footage in something close sRGB. The resulting target color space for the filmstock was not compromised by the gamut of the wall but by the recording color space of the scanner, thus we did not end up mapping the LED-wall primaries to sRGB because this would have severely limited the range of colors without being necessary. Instead, we used the same calibration we used for the Amira when shooting.

On a second test day, I specifically tested for the difference in color rendition between film and sensor in the lighting conditions of the LED- volume. To investigate whether one of the mediums would render metameric failure in skin tones less apparent than the other, a high-quality, broad spectrum LED panel (DMG MAXI MIX) was set up next to an RGB LED wall, both at 5600 kelvins. To merge the two lightsources into one key light, a ¼ WD frame was set up in front. Several lighting set ups were shot with both Kodak Vision 3 250d and an ARRI Amira recording ProRes 4:4:4 Log c, both with the same 50mm Zeiss Compact Prime CP2.

For the first setup, the scenes luminance came entirely from the broad spectrum DMG panel with the LED-wall blacked out. This defined the “optimal” skin tone for each medium, being exposed by only

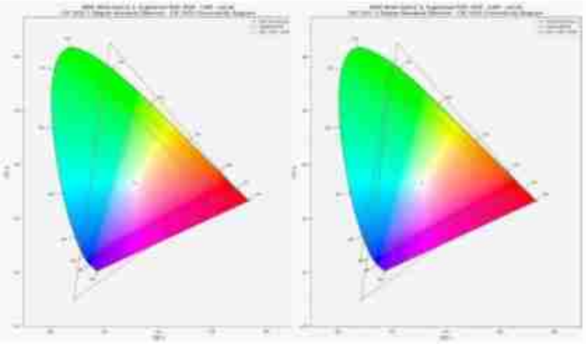


FIGURE 3.1.1: Measured color spaces for LED-wall Color Calibration

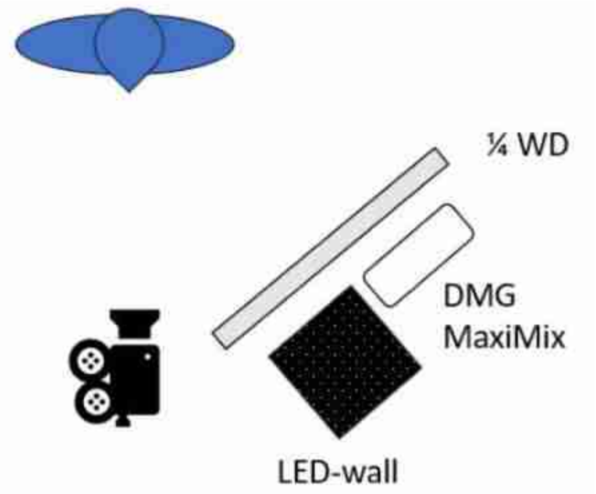


FIGURE 3.1.2: Color test setup

broad-spectrum light, thus preventing metameric failure compared to natural daylight. For every following set up, the DMG panel was dimmed down by 10 percent of the scene's luminance while the LED-Wall was dimmed up by 10 percent so the exposure of the key lit side of the model's face would stay at T2.1, matching the aperture of the lens. For every setup, the exposure and the color temperature stayed constant while the spectral power distribution drifted from even to narrow band.

The analog footage was processed and scanned at Studio L'Equipe in Brussels as DPX Cineon log 10 bit. The footage was compared with an ACES workflow. This way, the skin tones in the analog and digital footage for every setup could be compared to the respective "optimal" skin tone to judge which of the mediums would render metameric failure at what ratio of the scene's luminance coming from the RGB LED-wall. The results can be seen in figures XII to XXIV in the appendix. The measured spectrum for each setup is also visualized. An Evaluation of this test can be found in chapter 5.2.

3.2 Production

3.2.1 Technical Conditions

For the shoot we rented an ARRIcam Lite with a 3-perf kit aswell as an ARRI Amira. This way, we would have 16:9 35mm analog footage and 16:9 super 35 digital footage which would allow for an adequate analog to digital comparison with the same lens being used on both cameras and a similar depth of field due to the similar sized imaging plane. Since we conceptualized two zoom shots, I decided for the ZEISS lightweight zoom 21-100/ T2.9- T3.9. This choice also fit the requirement for a sharp lens that renders a relatively clean image without too much distortion or softness which would potentially reduce moiré and therefore misrepresent the test results. For a filmstock I chose Kodak Vision 3 250d since it has medium sized grain and fits the white point of the wall, which is also balanced on 5500k. Digitally, we would shoot ProRes 4:4:4 log C.

HYPERBOWLs LED-volume is 270 degrees oval shaped studio and measures 20m by 14m of floor space with 6m high walls. The ceiling is positioned directly on the edge of the walls and covers the entire volume. The LED-panels are ROE Diamond panels with RGB pixels and a pitch of 2.6mm. The video Bit depth is 10bit.

We would synchronize both of our cameras via genlock, which is part of the reason why we chose an Amira and an Arricam LT because they both have a BNC input that can receive genlock signal, which isn't common for film cameras. (The Arricam has a BNC in- port on the external speed box). However, whereas the Amira receives a trilevel HD sync signal, the Arricam receives an analog blackburst SD sync signal which meant the Arricam could not be synced with the ambient sync signal for the other components like the wall but had to be synced to an external Rosendahl sync generator that ran at the same pulse as the trilevel sync.

The LED-volume was set to run at 48 fps which is why we decided for flicker free LED lights which also had the advantage of being controllable via DMX. This way we could prevent flicker artifacts. Our lighting equipment consisted of 4 ARRI Skypanel S60 as top and fill light, an Aputure 1200d as key light, motivated by the moon, and an additional Aputure 300d and several Astera Tubes. For grip, we had a slider and a JanJib.

3.2.2 Prepday

On the prepday prior to the shooting day, the production design department built up a 1m high platform that was going to be our rooftop. This allowed for higher camera angles without seeing the floor of the volume that would have had to be painted out in post otherwise. Water puddles were added to the set to help tie the background and foreground together through reflections. Foreground elements such as antennas and smoke coming from a vent meant to give the scene additional depth.

Detecting double images in the flickering viewfinder when syncing the camera turned out to be quite difficult. To compensate, we held a smartphone camera to the eyepiece and recorded the image for a couple of seconds while rolling the camera without the magazine to safe film. We could then pause the video on the phone and look for double images in the still frame. Figure 3.2.2 shows the monitoring signal used with red bars running from frame left to frame right in the inner frustum. When off sync, double images would show as a second layer of semi-transparent red bars slightly shifted to the side.

To save time on the shooting day, we decided to expose the scene for 200 ISO and shoot at 400 ISO and an ND 0.3 in the Amira. That way, we wouldn't have to relight when switching the camera. Keeping the same light for both mediums would also assure

FIGURE 3.2.1: A lighting setup in the volume

comparability. Additionally, we would overexpose the film by a quarter stop which would give us some latitude to not unintentionally underexpose the film when shooting the dark night scene.

In prelight, the main goal was to match the colors and contrast of the virtual and the physical scene. Since we were going for a high contrast night scene with an undiffused moonlight as key light for the virtual scene, we had the problem that the black levels of the wall didn't go as low as desired. This meant that we had to lift the overall brightness of the wall to create the right contrast ratio. For the physical set this meant also raising the brightness (key and fill) to get the same matching values to the wall. However, we did not have enough output from the key light to do so. We could have raised the overall level of the scene with our fill light to get matching brightness but then the contrast ratios of the virtual and the physical environment would have been off. In the end, we settled for a lower contrast ratio (the highest we could achieve with the limitations of the black levels of the wall and the power of our key light) to match physical and virtual scene as much as possible and then steepening the contrast in post.

To get the desired look, we adjusted the color values of the night sky and other parts of the virtual scene and matched the color of our key and fill light accordingly. Since we did not achieve the LUT for the AMIRA to be able to use it as a viewfinder for the ARRICAM in preproduction, we judged the values on the entire wall by eye. By doing so and not looking through the viewfinder, we didn't realize that we only graded the

FIGURE 3.2.2: monitoring signal for synchronization

outer frustum, thus only impacting the ambient light in the scene but not the actual background color in the frame.

3.2.3 Shooting Day

We shot every single shot digitally first to get the acting and the camera movement until the director was happy and then switched to the film camera.

By provoking moiré artifacts, unconsciously, we also created additional problems we did not account for. In the pan of shot 2.3, the problem was one of unrealistic motion blur. If this was filmed on location, the camera would film a continuous movement and intercut it into 24 images. The rooftops would be gittering because of the framerate and have motion blur because they'd be moving in each frame (relative to the camera). The birds however wouldn't have motion blur nor would they gitter if the pan of the camera is matching their speed thus negating their motion relatively speaking. In the volume however, unreal didn't accurately recreate these physical parameters. The motion blur in the background is the same for every layer of roofs since they are all projected on the same plane, whereas they would have increased motion blur the closer they are to the camera on location. The birds also had motion blur or smeering artifacts possibly caused by Temporal Super Resolution in Unreal Engine.

Shot 2.4 included a zoom from 100mm to 30mm. This meant the inner frustum had to enlarge during the shot to account for the widening field of view. Setting the frustum to the size required at 30mm from the beginning would not have worked since the background compression of the virtual environment would not have matched that of the long lens. To realize this shot, a zoom sequence of the virtual camera was programmed and then manually triggered to be in sync with the zoom of the physical camera.

Shot 2.5 on the other hand created problems for the performance of the wall. Since the spatial limitations of the studio forced us to use a 12mm wide-angle lens to realize this shot, this meant the frustum had to cover a large part of the wall and needed a lot of computing power. This led to the GPU eventually crashing. Also, the wide-angle lens made us have the truss the actor was rigged on as well as the lights in frame which made this a post-heavy shot. Due to the technical holdup, we did not manage to get this shot on film.

3.3 Postproduction

3.3.1 Processing and Scanning

After the shoot we sent the negatives to Studio L'Equipe in Bruxelles, Belgium, for it to be ECN2 processed and scanned in 3k resolution with the ARRISCAN. The output files were DPX log 10 bit.

3.3.2 VFX

For potential VFX work we had recorded the inner frustum directly from Unreal for every shot, so if there would be any image artifacts in the background, the compositing artist could rotoscope the actor from the background and replace it with the recorded inner frustum. The VFX artists would then have to recreate what the lens and the recording medium would have done to the background as if it had been projected by the wall and filmed by the camera with the help of a grain plate and lens grids we had filmed on set.

This was also important for shot 2.5 that we had only gotten digital and had to match it to the rest of the analog footage. In Shot 2.5, we cropped the image to the point where the truss and lights were not in frame anymore and layed it over the recorded inner frustum. After replicating the distortion and other characteristics of the lens to the background plane so the overlaying images would merge seamlessly, we used the grain plate to match the look to the analog shots.

In Shot 2.3, the unrealistic motion blur was quite apparent which is why we used the recorded frustum for the pan and merged it with the end of the shot we filmed with the actor. In the pan, we applied the same principles of replicating the characteristics of lens and medium to make the transition seamless.

3.3.3 Color Grading

In the grade, we pulled every shot by one or two stops to get it to the right brightness. To make up for the grayish sky (since we only graded the outer frustum on set), we pushed it towards blue and increased the brightness of the stars so it would look like a clear night sky. The magenta tint was also corrected. Since the key light was lacking output relative to the black values of the wall as explained above, we had not managed to match the foreground and background colors close enough (as can be seen in figures I to V) and used a depth map to compensate. In the shots we used the digital footage or recorded frustum, we emulated the colors of the film as closely as possible.

4. RESULTS

The final end product of the shoot is a one-minute social spot shot (almost) entirely on film. Only the scene on the rooftop was shot in a volume, however. The clip can be found on the CD attached.

Figures I to V in the appendix show a film vs digital comparison of Vision3 and Amira footage of the shoot. The stills were white balanced to the color checker. A comparison of film and digital concerning moiré (figure VI to XI) and color rendition (XII to XXIV) can also be found in the appendix.

5. DISCUSSION

5.1. Moiré

Even though moiré physically can't occur on the film negative by plainly filming the wall, the problem of potentially capturing this image artifact is not gone. Moiré can still occur in the digitized footage when the negative visibly renders the pixel pattern of the LED-wall, since the scanner, itself using a digital sensor, provides a second grid pattern that potentially interferes with the pattern captured on the negative, depending on the relative frequencies of the pattern captured and the frequency of the scanning sensor.

In the footage shot for this paper, the MTF of both recording systems was high enough to detect the pixel pattern of the LED-wall in both the test (setup 1) and the shoot (setup 2) in the instances the camera was focusing the wall. On the test (setup 1), the cameras were positioned about 2 meters from the wall with a 32mm lens and on the shoot (setup 2), the cameras were about 6 meters away from the wall and had a 100mm lens attached. Hence, in both setups the pixel grid was large relative to the senor / the film.

In the Amira footage, there was no moiré but a fully resolved grid pattern in setup 1, and moiré in setup 2 (figure VI and X). In the negative of both setups, there was a resolved grid pattern. Setup 1 was first scanned with the 4k Cintel scanner resulting in moiré (figure VI), then with the ARRISCAN in 3k resolution, resulting in a fully resolved grid and then again with the ARRISCAN in 6k resolution, also resulting in a fully resolved grid. Setup 2 was only scanned with the ARRISCAN in 3k resolution and resulted in moiré. It's important to note that these artifacts can be difficult to judge since they are most apparent as a flickering in the moving image and therefore might not appear accurately in the stills in this document. Moreover, different down- or up sampling algorithms in the editing software, compression and potentially even the resolution of the display screen in use can impact the result heavily (figure VIII to XI). With different down sampling algorithms, the 6k scans were more prone to recreate moiré artifacts. However, this is an inherently complex topic of its own and for the sake of this thesis will not be treated any further.

It concludes that scanning at high resolutions can prevent moiré when exceeding the necessary sampling frequency according to Nyquist, however, it can also amplify the image artifact when the resolution still isn't sufficient. The low-resolution scan seems to act as a low pass filter, filtering high frequency patterns from the negative. A well-chosen scan resolution is either sufficient to fully translate the LED-wall grid

structure from the negative in the digitized image which can be compensated by a correct down sampling algorithm or blurring, or low enough to filter the grid pattern resolved from the negative while retaining sufficient image quality for the delivery format.

The key factor here seems to be the sampling resolution, not the irregular grain pattern. Hence, similar results could be achieved shooting digitally. Film as a recording medium can still be considered beneficial since moiré artifacts are not "baked" into the image like when captured digitally. The footage can be scanned in different resolutions with trial and error to get the best results, while the "correct" sampling resolution practically can't be predicted on set when shooting digitally since it`s different for every scenario. (Even looking at a monitor on set might not be reliable since the display might impact the apparency of the artifact as explained above). When noticed in the image when shooting digitally, changing the resolution (when not wanting to make compromises on framing and lens choice etc.) could help prevent the image artifact.

Another argument that can be made in favor of film is the MTF. Every component in the imaging chain has an own MTF, hence reduces contrast, especially when sampling high frequencies. When shooting a side-by-side comparison of an analog and a digital camera with the exact same combination of lens, distance and angle to the wall, and matching MTF and sampling frequency of sensor and scanner, the scanned footage will still be less likely to render moiré artifacts since the additional component of the film negative, itself also reducing the resolution, will provide additional blur, especially in high frequency part of the frame. Whereas the sensor might render moiré under those conditions, the scanner might not since the negative might have, especially due to its thickness, blurred the grid of the LED-wall to the point of undetectability, hence making it impossible for the scanner to interfere with the grid of the wall. However, this setup and the assumption that the MTF of both systems are the exact same is highly theoretical.

In a nutshell, the difference concerning moiré does not seem to be big enough for film to be creatively liberating when conceptualizing shots. Especially since focusing the wall, e.g., is still not advisable due to other artifacts and a lack of depth.

Scanning the negative with a device that uses CCD chips instead of a CMOS sensor could also help minimize moiré since the photosites in CCD chips are more densely positioned, resulting in a higher sampling frequency, and are and therefore less prone to produce aliasing artifacts (Schmidt, 2013, p. 377). Examining the behavior of a TDI scanner (Time Delay and Integration) could also proof beneficial.

SILBERSALZ even provides a 14k scanner, utilizing a 150 MP PHASEONE sensor, which is also likely to largely prevent moiré.

film footage of the test day (setup 1) scanned with 3k ARRISCAN, original resolution and cropped in with fully resolved pixel grid

film footage of the test day (setup 1) scanned with 6k ARRISCAN, original resolution and cropped in with fully resolved pixel grid

5.2 Evalution of the colors with Colorist Steffen Paul

Steffen Paul in a Berlin based Colorist who has worked in the industry for over a decade. He has worked on numerous productions such as the Netflix series Dark (2017) and 1899 (2022) as lead Colorist. Since 1899 was entirely shot in an LED- volume, he has experience with grading volume footage and handling the occurring metameric color shifts. He has analyzed the color test and compared the analog and digital footage of the shoot.

Figures XXII to XXIV show Steffen Paul's technical grade of the color test. The footage was worked with in ACEScct AP 1 and output to rec 709. The Amira footage for each setup was white balanced to the neutrally gray wall in the background and showed strong metameric failure, in both the skin tones and the color checker, increasing in apparency for each setup (figure XII to XXII). To compensate, Steffen Paul used a color correction matrix and increased the saturation by around 20 percent for the last ("worst") setup to match it to the first ("optimal") setup as much as possible. Each other setup was graded with the same method, with less correction needed the more light came from the broad spectrum light source. Even though this method resulted in almost matching colors, a shift in brightness prevailed (figure XXIV). (It should be noted that this shift in brightness could have been visually amplified due to the setup of the light sources side by side and the diffusion not being strong enough to accurately merge the two light sources creating differing reflections on the color checker.)

The digitized analog footage had a magenta tint, especially noticeable in the footage shot in the volume. The footage underwent the same procedure as the digital footage, however, after white balancing, the magenta tint disappeared, and no additional correction was needed to match the footage for each setup. Both the color checker and the skin tone stayed consistent for the differing lighting spectra whereas the Amira footage needed severe correction (figure XII to XXIII).

Steffen Paul concludes that the digitized negative did preserve more color information than the Amira and rendered the scene more consistent, being less sensitive for metameric failure in the lighting conditions of the test. (figure XXII and XXIII) This is most likely related to the response curves of the filmstock being "broader" than the response curves of the ARRI Amira. He also mentions that such color tests, especially a comparable optimum for a lighting situation (e.g., real overcast daylight) for a scene shot in an LED-volume can be of great value and proposes to shoot such in preproduction. These can be used as a grading reference in post, showing the behavior of skin tones under a specific lighting condition if it were shot on location and not emulated by RGB LED- panels.

Judging the results of his technical grade visually, metameric failure becomes especially apparent in the digital footage at 80% luminance from the RGB source (figure XX). At 100% luminance from the RGB source, metameric drifts are apparent in both mediums, however, much more so in the Amira Footage (figure XXII and XXIII). To evaluate this color shift mathematically, I would propose to normalize the data and compare it via .E, a measurement type standardized in 2000 by CIE that quantifies the apparency of color shifts. The behavior of varying skin tones under these lighting conditions should also be analyzed.

In the conditions of the shoot, too much additional, broad-spectrum light was used to pinpoint a difference in metameric failure to the recording mediums. The lack of an "optimum" for both recording mediums in the specific lighting conditions made the shift hard to judge. Still, Steffen Paul found the analog footage to look promising in terms of color rendition.

When setting up a color calibration of the LED-wall for a given filmstock, a film scanner with a wide recording gamut should be chosen, to let the digitized footage of the primary patches represent the recording color space of the negative as closely as possible. The film footage of all scenarios had a magenta tint, yet seemingly being amplified in the footage shot in the LED-volume. This could have possibly been prevented with an accurately set up color calibration between filmstock and LED-wall.

In conclusion, the rendition of colors in an LED-volume consisting of RGB LED-panels seems less problematic in a film pipeline. Still, Elaborate tests of this behavior should be done in pre-production since this behavior could differ in other lighting conditions or for other film stocks. According to such tests, ways to minimize the problem can be found like through the lighting concept but also through the color calibration. Since Volume setups with RGBWW LED-panels (Red, Green, Blue, Warm White) are already in development, this problem could soon be less relevant since these types of panels provide a more even spectral power distribution resulting in less metameric drifts.

In the following are two exemplary results of the test concerning color rendition and metameric failure, the other of which are to be found in the appendix.

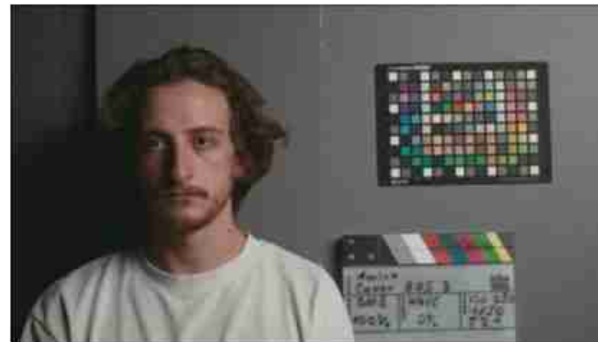
Amira footage of the color test, white balanced

"worst" setup

"optimal" setup

Film footage of the color test, white balanced

"worst" setup



"optimal" setup

5.3 Workflow

In preproduction, the workflow was more complicated than when shooting digitally in an LED- volume. This was especially noticeable in the process of calibrating the LED-wall to the filmstock. To calibrate the LED- wall, the analog footage of the primary patches needs to be processed and scanned to compare the values and set up the color correction matrix which means additional steps are necessary and the calibration can't be done immediately on set. When re-examining the result for successful calibration, the same steps are necessary resulting in multiple iterations with processing and scanning in between to ensure accurate color calibration. This makes it a time-consuming task.

While tracking systems work in the exact same way, synchronization requires workarounds and more time but ultimately does not pose a serious problem if the analog camera has a way to receive a synchronization signal.

On set, the most impactful difference is the monitoring. Not having an immediate, reliable image to judge, in certain instances, is hindering creative work since the departments, especially lighting, Brainbar and the DP are standing on set guessing. This is not as much of a problem when executing the shots precisely as planned and tested. However, making spontaneous decisions due to unforeseen aspects like an actor's performance or the discovery of a new shot idea on set could potentially recreate image artifacts that were meant to be avoided by testing critical shots in advance. As mentioned, being inventive on the day generally comes with complications when shooting in a volume. However, even more so when shooting on film since the lack of a reliable camera image makes monitoring a newly thought up shot regarding image artifacts impossible or at least significantly harder.

The lack of reliable monitoring seems to outweigh potential minor advantages of film concerning moiré. Being able to judge the image on set and adjust camera position and framing in accordance is more likely to prevent image artifacts than the characteristics of film. With more time in Preproduction, most occurring problems could probably have been prevented.

6. CONCLUSION

While film can certainly help push the boundaries of what is technically possible in an LED- volume, it does not redefine them. The volume will still prove to be the right tool for certain situations and unsuitable for others.

Film will most likely reduce moiré, but it only partially frees the camera by doing so, since having the LED-wall in focus still risks unrealistic depth of field or motion blur, aswell as moiré by scanning if the film negative visibly renders the grid structure of the wall. When conceptualizing shots with the LED-wall in focus, great care must be taken to avoid these other problems. When tested properly in advance, celluloid can help to make shots work that would not when shooting digitally.

Concerning the rendition of color and metamerism, further tests should be undertaken to give definitive answers whether the characteristics of film benefit the spectral conditions of a volume, since color pipelines are extremely complex. However, in the tested conditions, film proofed very beneficial and outperformed the digital footage, rendering little to no metameric failure and preserving more image information for color grading. The organic, grainy film-look or anisotropic rendering also proved to be an advantage. However, this characteristic could possibly be recreated in color grading.

The most relevant drawback of shooting film is the lack of immediate, reliable way to monitor the image. Even though this is common practice when shooting on film, it partially negates one of the primary arguments for shooting in a volume (WYSIWYG) since you barely see what you get. This combination of tools gives production crews the ability to control every parameter like the environment itself, colors, and contrast, without offering a solution to properly monitor these. Thus, more time in preproduction is advisable to test critical shots, prevent moiré and color rendering issues and set up the color calibration between the LED-wall and the filmstock.

In a nutshell, shooting film in an LED-volume is certainly possible and potentially even minimizes image artifacts and color rendition errors of digital nature when properly tested in advance. Still, this only liberates the cinematography to a certain extend since the lack of an accurate live camera image doesn`t allow for reliable monitoring. This may result in increased creative freedom when conceptualizing shots but less creative freedom when standing on set. Extensive testing in preproduction is key to successfully shoot film in a volume. Further scenarios need to be tested to fully comprehend the potential of shooting film in an LED- volume.

List of acronyms

LED – Light Emitting Diode
CGI – Computer generated imagery
DP – director of photography
VP – Virtual Production
MPC – Moving Picture Company
ICVFX – In-Camera Visual Effects
SMPTE – Society of Motion Picture and Television Engineers
HMI – Hydrargyrum medium-arc iodide lamp
CMOS – Complementary Metal Oxide Semiconductor
CCD – Charged Couple Device
VFX – Visual Effects
DIT – Digital Image Technician
WYSIWYG – What You See is What You Get
OLPF – Optical Low Pass Filter
MTF – Modulation Transfer Function
OCIO – Open Color IO
RGB – Red, Green, Blue
ACES – Academy Color Encoding System
CIE - Comission Internationale De L'Eclairage
LUT – Look Up Table

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LIST OF FIGURES

APPENDIX

Figure I: analog to digital comparison shot 1, own image

Figure II: analog to digital comparison shot 2, own image

Figure x: analog to digital c

Figure III: comparison shot 3, own image

Figure IV: analog to digital comparison shot 4, own image

Figure V: analog to digital comparison shot 5, own image

(analog footage missing)

Figure VI: moiré comparison 1

Amira footage of the test (setup 1) day original resolution cropped in with fully resolved pixel pattern

film footage of the test day (setup 1) scanned with 4k Cintel scanner, original resolution cropped in with visible moiré

Figure VII: moiré comparison 2

film footage of the test day (setup 1) scanned with 3k *ARRISCAN*, original resolution and cropped in with fully resolved pixel grid

film footage of the test day (setup 1) scanned with 6k *ARRISCAN*, original resolution and cropped in with fully resolved pixel grid

Figure VIII: moiré comparison 3

film footage of the test day (setup 1) scanned with 3k *ARRISCAN*, down sampled “sharper” to 1080p and cropped in with slightly visible moiré in the moving image

film footage of the test day (setup 1) scanned with 6k *ARRISCAN*, down sampled “sharper” to 1080p and cropped in with amplified moiré

Figure IX: moiré comparison 4

film footage of the test day (setup 1) scanned with 3k *ARRISCAN*, down sampled “smoother” to 1080p and cropped in with slight moiré in the moving image

film footage of the test day (setup 1) scanned with 6k *ARRISCAN*, down sampled “smoother” to 1080p and cropped in with amplified moiré

Figure X: moiré comparison 5

Amira footage of the shoot (setup 2), original resolution with visible moiré

film footage of the shoot (setup 2) scanned with ARRISCAN 3k, original resolution with visible moiré

Figure XI: moiré comparison 6

film footage of the shoot (setup 2) scanned with *ARRISCAN* 3k, down sampled “sharper” to 1080p with amplified moiré

film footage of the shoot (setup 2) scanned with ARRISCAN 3k, down sampled “smoother” to 1080p with amplified moiré

Figure XII: DMG: 100%, LED-wall: 0%, images white balanced, own images