Optics of Digital Cinema

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ABSTRACT

The wide acceptance of digital cinema depends on the ability of the projector to at the very least match film in color gamut, contrast, brightness, and resolution consistently. In most cases, digital projection is expected to even outperform film as a requirement for switching from film to digital because of digital projection cost. This paper examines DLP™ based digital projection and the optics required to produce an acceptable digital image that exceeds theatrical release film. Optical path efficiencies, tolerances, coating properties and the DMD™ are important parameters for color, brightness, contrast, and uniformity of the image. The efficiency and tolerancing of the optical system are key drivers for obtaining consistent high brightness and uniformity, while coatings and the DMD™ mainly affect consistency in color and contrast. DLP Cinema™ projection, based on the optics discussed, is shown to deliver a stable color gamut slightly smaller than film having consistent uniformity <300 K across a native white image with consistent brightness of 12 ft-L on screens up to 15 m. The contrast and resolution are native to the DMD™ but contrast can be influenced using apertures in the lenses and illumination system. Contrasts up to 3000:1 on/off are possible by the use of asymmetric apertures. These results are compared to the color gamut, contrast, brightness, and resolution of typical theatrical release film.

Keywords: digital cinema, projector optics, DLP cinema

1. INTRODUCTION

In the last 7 years, with the introduction of the Texas Instruments DLP technology, a truly digital means of projecting an image with the performance to match and exceed film was introduced to the film community[1, 2]. The TI digital micro-mirror device (DMD) showed the potential for high resolution, contrast, brightness, and most importantly the potential to match the color gamut of film.

In its current form, DLP cinema is based on 3-chip projection. 3-chip was chosen over 1 chip for the necessary higher brightness, electronic cinema processing requirements, and lack of color separation artifacts present in 1 chip projectors. The TI DMD consists of an array of 1280x1024 tilting micro-mirrors as shown in figure 1. Each mirror has a pitch of 17 micrometers and tilts ±10 degrees along the diagonal. A micro-hinge under each mirror connected to a CMOS circuit beneath provides the electrostatic actuation.

In operation, the illumination system is set-up to illuminate the DMD at an off-axis angle as shown in figure 2. When the DMD is at –10 degrees the illumination light is reflected into the projection lens. When the DMD rotates to +10 degrees the illumination light is directed away from the lens. The imaged pixels appear on the screen as either bright or dark. In between, is a flat state which results as the micro-mirrors rotate from on to off. For 3-chip systems, a color splitting-combining prism is used to split color into red, green, and blue for each DMD. The DMD's use pulse-width modulation to generate color intensity and are capable of up to 15 bits of color depth. This allows over 1 trillion colors to be displayed. Apart from generating the image, the DMD also primarily controls the contrast that is possible in DLP cinema. The limitations to the contrast are due to diffraction and scattering from the mirror vias and the mirror gaps[3]. In the off and flat state, these contributions can be scattered and reflected into the projection lens resulting in reduced contrast.

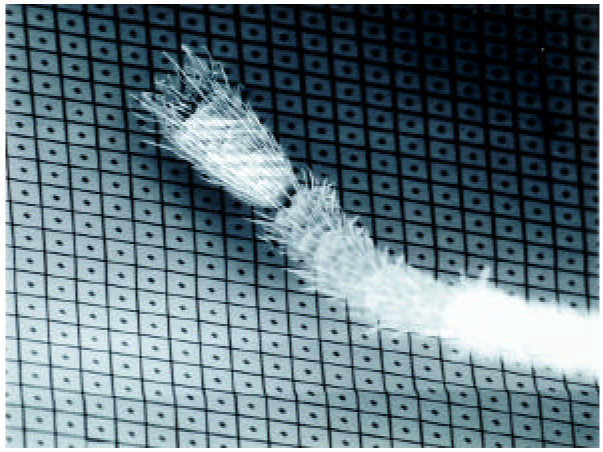

Figure 1: Picture of DMD showing micro-mirrors relative to an ant leg (courtesy of Texas Instruments Incorporated).

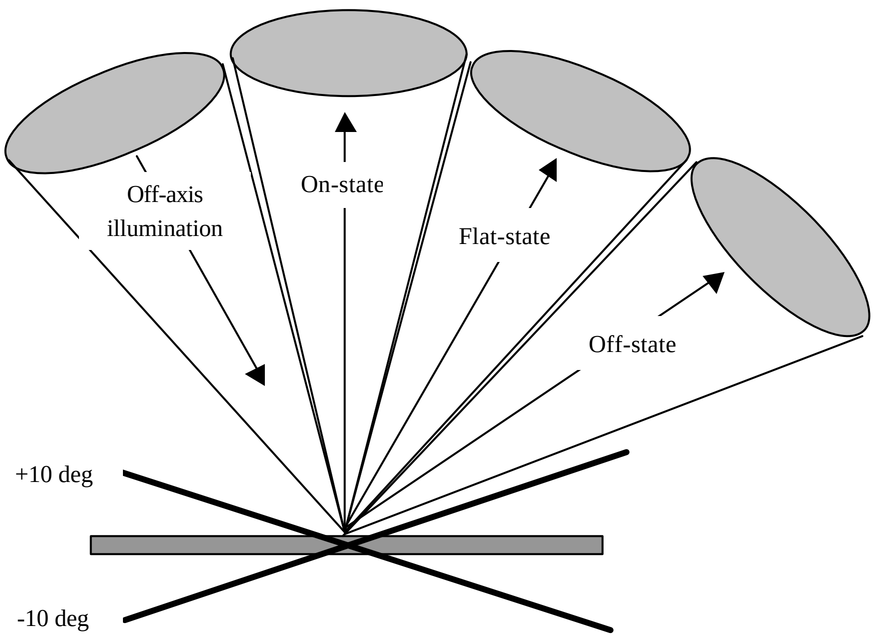

Figure 2: Off-axis illumination of DMD is used to separate on-state, flat-state and off-state.

Although the DMD is the primary imaging device, the optical design of the illumination system and projection optics provides the brightness, uniformity, and color gamut in the image as well as contribute significantly to the contrast possible with a DLP cinema projector. The design and tolerance of the optical system strongly influences color, brightness, and contrast.

This paper examines the optics and optical coating requirements necessary to realize the performance of the current 1280 x 1024 TI DLP cinema DMD and compares the performance results with typical theatrical release film.

2. OPTICAL PERFORMANCE AND CHARACTERISTICS

In the typical DLP cinema projector shown in figure 3, the optics can be divided into five groups: light source, UV/IR management, illumination optics, color control, and imaging. The light source used is always a Xe lamp in combination with a reflector. Xe lamps are chosen for their near-cinema color temperature of 6500 K and their excellent color stability. In addition, they are available in multi-kilowatt configurations enabling illumination of screens up to 25 m wide. As an example, Xe lamps in the 3 KW to 7 KW range are typically used in the cinema environment. For such high powers, significant filtering of UV and IR is necessary to protect the DMD. Two UV filters and two IR filters are used to reduce the levels of UV/IR to acceptable values at the DMD. The illumination optics consist of an integration rod and relay lenses. The rod has the same aspect ratio as the DMD and homogenizes the focused light from the lamp. The relay lenses form a telecentric illumination system and image the output end of the rod on the DMD. Telecentric illumination is used because it provides better uniformity of light on the DMD and also reduces distortion of the illumination due to a lower illumination angle. Color gamut is achieved with a 3-chip prism and a color notching filter[4]. The prism and filter notch out cyan and yellow to produce a color gamut similar to film. Imaging is done by a telecentric projection lens since the illumination system is telecentric.

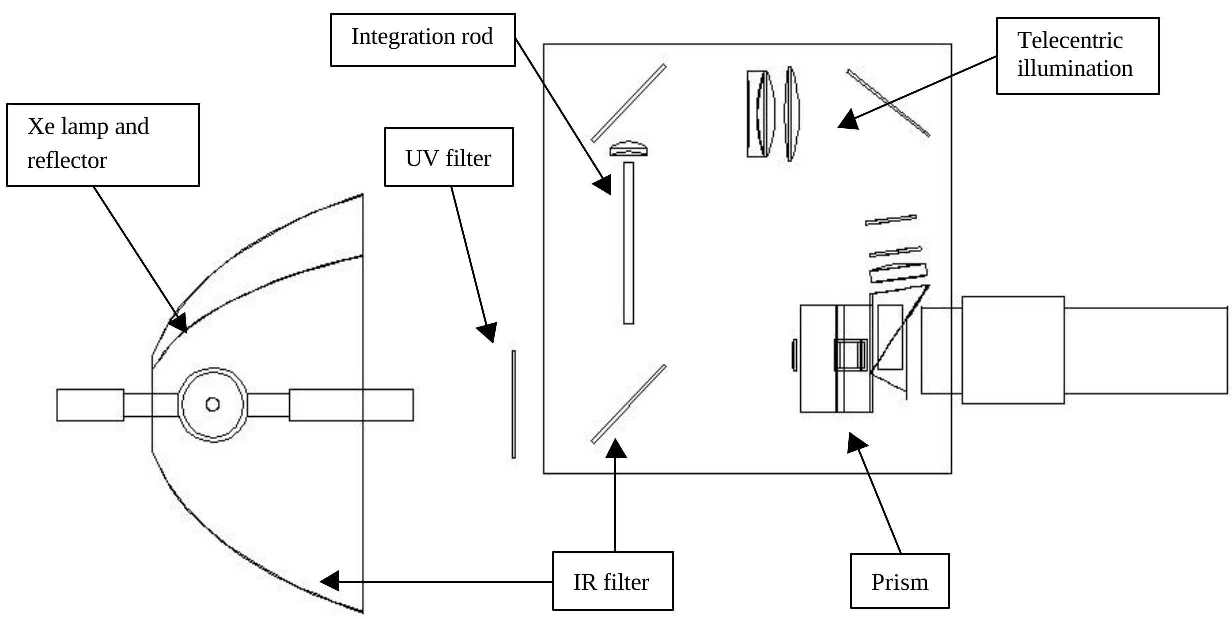

Figure 3: Optical layout of digital cinema projector showing the illumination optics and the various filters for UV, IR and color notching

2.1 COATING PROPERTIES AND TOLERANCING FOR COLOR

The most important parameter for DLP cinema projection is the color gamut. In a typical DLP projector, a color splitting-recombining prism determines the attainable color gamut. The design of the prism is shown in figure 4.

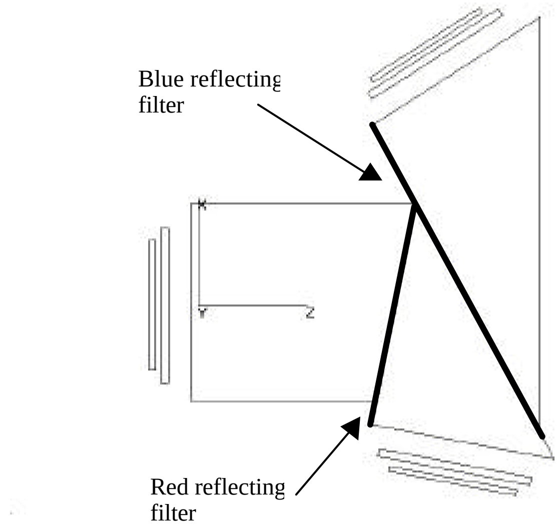

Figure 4: Prism design for DLP projection showing the red and blue dichroic filters

Since the DMD’s tilt to generate the on state and off state, the illumination light that passes through the filters does so at a different angle than the on-state light that is reflected back through the filters and to the projection lens. The dichroic shifting of the filters naturally notches out yellow and cyan colors in the prism. This results in the typical DLP color gamut shown in figure 5.

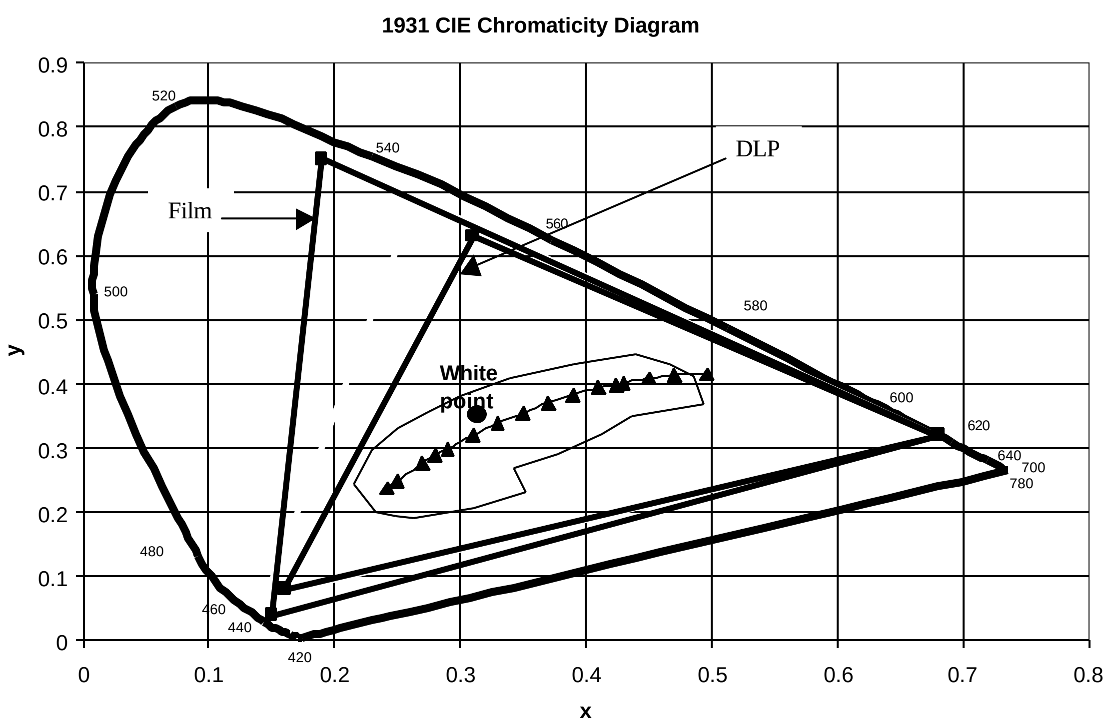

Figure 5: Color gamut of standard DLP vs typical film

Also shown is the color gamut of film and the typical white point. Typically, the white point will be near x=0.314, y=0.351 corresponding to ~ 6300 K on the blackbody curve. Most film content is matched for this white point but can range or vary as low as 5400 K. In order to better match the gamut of film DLP cinema projectors use a yellow notching filter[4] to remove more yellow and cyan from the spectrum of the Xe lamp and match the typical white point. This results in a more cinema like color gamut shown in figure 6. The DLP cinema color gamut lacks the deep greens and cyans that can be attained with film but closely matches the blue and red color primaries very well as well as the white point. The lack of deeper greens and cyans has not been a concern for the film community primarily because DLP cinema has proven to be able to reproduce film like color satisfactorily.

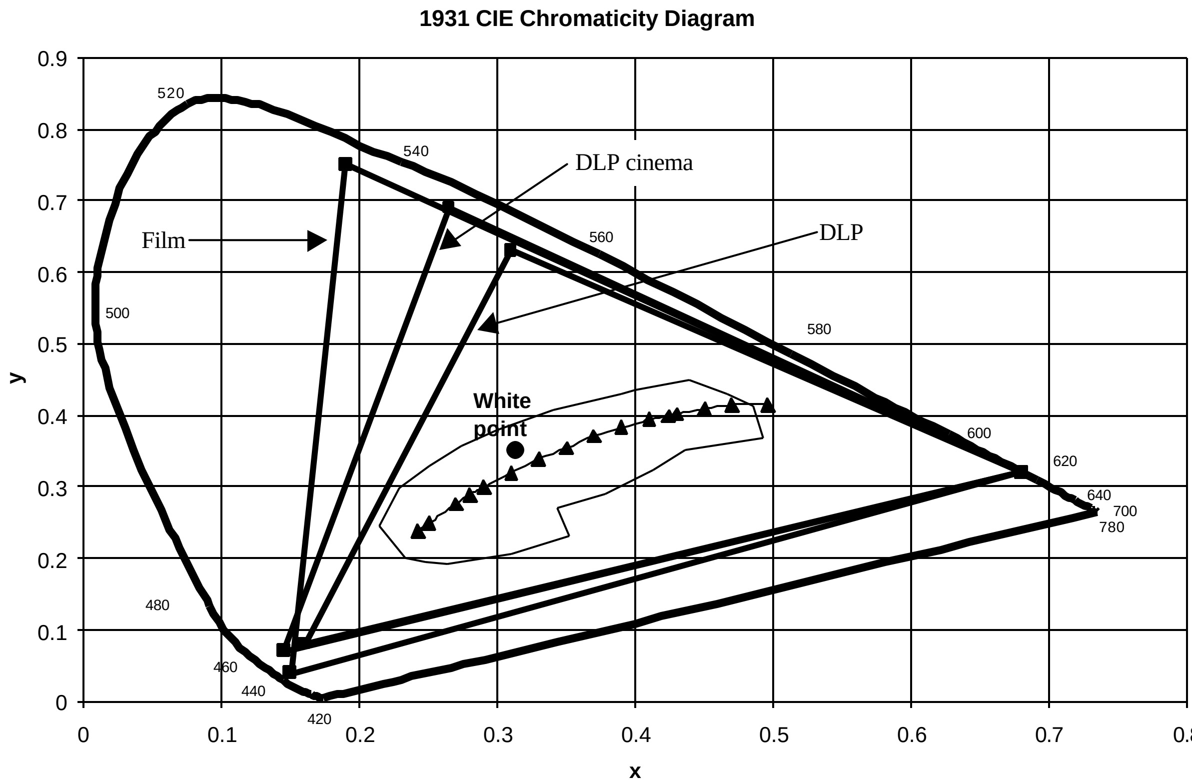

Figure 6: DLP Cinema color gamut showing the deeper green primary color

The use of a notch filter to increase the size of the color gamut has the drawback of decreasing the available brightness from the projector due to the yellow notch. Typically, 25% reduction in brightness efficiency is expected for DLP Cinema. Using optical coatings to generate the color gamut implies that a given projector will have a stable color gamut over time and will be able to display the exact same color regardless of the content. However, optical coatings have associated tolerances and therefore DLP cinema processing electronics are used to color correct projectors so that each projector generates the same color. The process of color correction can also reduce brightness efficiency because color can be electronically removed to generate the desired color space and white color points for DLP cinema. In addition, contrast is affected by color correction as well since color correction reduces the white levels of the projector but not the black.

To minimize the brightness and contrast loss, optical components must be well toleranced. In figure 3, tolerances in the UV filters, IR filters, reflectors, and AR coatings all contribute to variations in the white color point. This is because the transmission or reflectance is relatively easy to control but the cut-on and cut off bands of the various filters are more difficult to tolerance. Shifts in the cut-on and cut-off bands of the UV and IR filters including the lamp reflector can contribute to a shift in color temperature of 500 K. Tighter tolerancing of the cut-on and cut-off on the order of +- 7 nm can reduce the shifts to 200 K. The notch filter and prism are more difficult to control due to complexity and limitation of design and manufacture. These components not only contribute to white point shifts but also affect the color primaries. Figure 7 shows the spectrum of a typical yellow notch filter used in a DLP cinema projector.

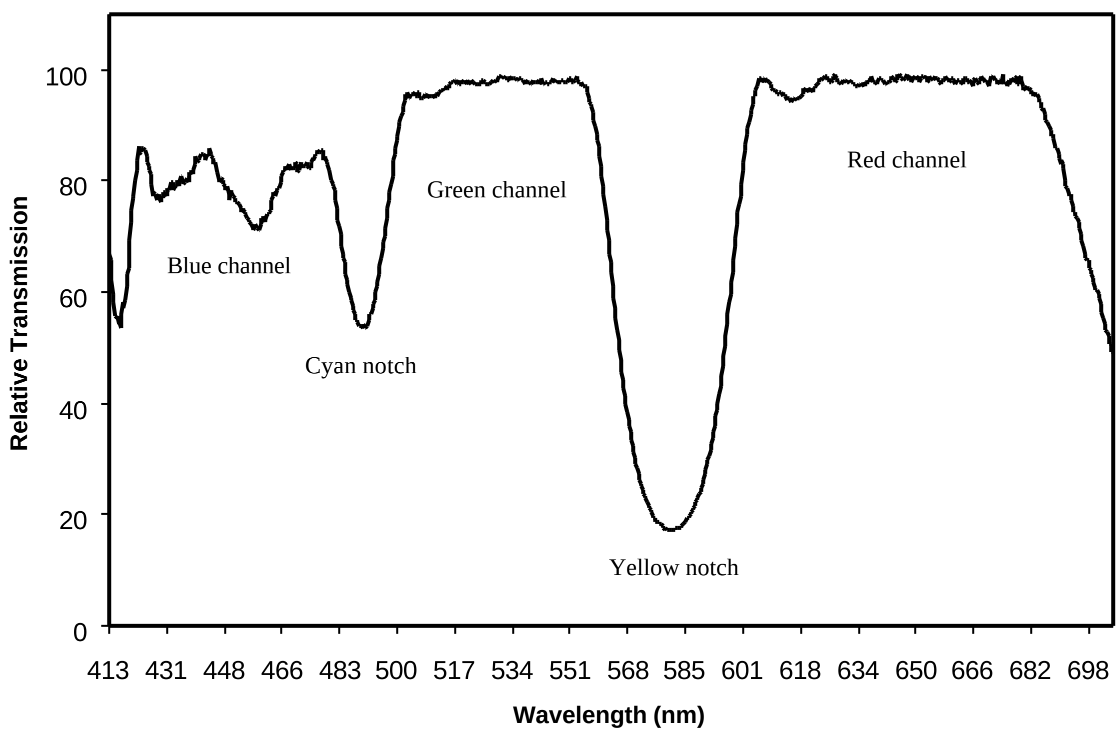

Figure 7: Typical yellow notch filter[4] used to increase color gamut for DLP cinema projectors.

The filter has three pass bands, blue, green, red and two notches cyan, and yellow. The transmission in each pass band sets the white color point for the projector and is calculated from the overall optical transmission of the projector without the yellow notch filter. The primary color points in the color gamut are set by the cyan and yellow notches in figure 7. The notches are fairly simple to control and specify. Tolerances of +- 5 nm have to be ensured to limit the variation in the primary colors to that specified for the DLP cinema electronic color correction. Transmission intensity in this filter design is difficult to control. Oscillations result from the complex design and are prominent in the blue channel. With careful coating design and specification, the oscillations can be controlled to +- 5% around the average transmission in the blue channel. Figure 8 shows the calculated variation that can occur around the typical white point x=0.314, y=0.351. This corresponds to approximately 300 K color shift in the white point. Using DLP cinema electronic color correction, the exact white point can be matched with a maximum loss of 10% to brightness and contrast. The prism has similar contributions to the yellow notch filter. Although only two dichroic coatings are required to split off blue, green, and red colors, there are 11 other surfaces including a TIR block that are anti-reflection coated. Variations in these coatings in the blue region of the spectrum also cause a color shift in the projector white point. This also contributes to the brightness and contrast loss of the projector but is smaller than the contribution of the yellow notch filter.

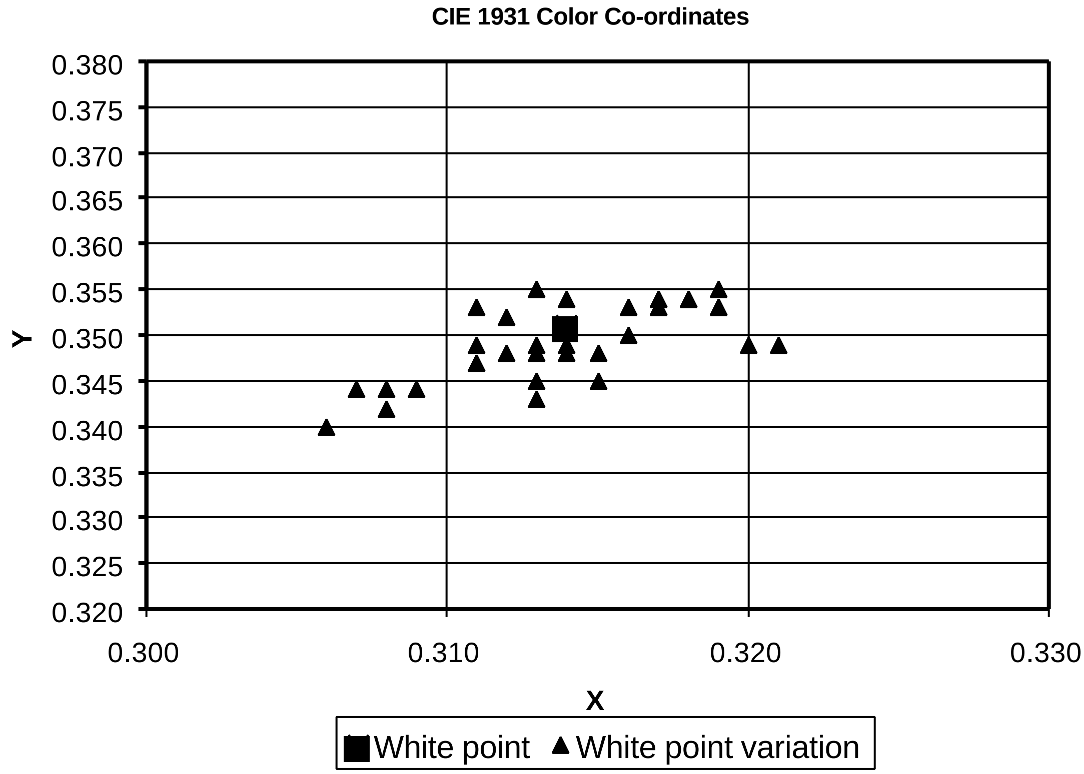

Figure 8: Color chart showing the variation that occurs in the white point as a result of oscillations in the transmission of the yellow notch filter.

2.2 OPTICAL TOLERANCING

Optical tolerancing contributes to brightness and brightness/color uniformity. The telecentric illumination system in figure 3 magnifies the image of the output end of the integrator rod onto the micro-mirrors at the DMD. Under ideal conditions, the magnification is matched to just fill the entire active area of the DMD with illumination light. However, positional and optical surface tolerance produces a tolerance in the magnification. This requires that the DMD be overfilled with illumination light. The overfilling contributes to brightness loss since the over-spilled light does not reach the image screen. In typical illumination design up to 5% of the illumination light can be lost. Tighter tolerancing can recover the lost light but the trade-off in optical cost is usually too high for 5% gain in light.

Brightness and color uniformity is mostly due to the alignment between the lamp focus and the integrator rod. For DLP cinema, 90% illumination in the corners of the image and 300 K color shift across the screen image can be achieved with good alignment of the illumination light. Typically, perpendicularity between the input of the integrator rod and the lamp focus should be within 20 arcmin.

2.3 CONTRAST

The ability of the DMD to separate flat state light from on state light due to the amount of scattering and diffraction determines the limit of contrast possible. However, the contrast can be further improved with the use of apertures in the illumination and projection lens[3]. DLP cinema currently uses an asymmetric aperture in the projection lens. The aperture is located at the field stop and limits the f/# of the projection lens in the direction of the DMD tilt. This limits the amount of scattered and diffracted light from the flat state that can enter the projection lens. With this technique DLP cinema projectors currently achieve up to 1500:1 contrast. This is approximately a 500:1 contrast improvement over that achievable with the DMD alone. There is a trade-off of 8% brightness loss for this contrast increase. Further increases in contrast can be achieved with apertures in the illumination system[3]. By placing an asymmetric aperture at the field stop of the illumination system in figure 3, the f/# of illumination can also be limited in the direction of the DMD tilt angle. This further limits the amount of scattered and diffracted light that enters the projection lens. With the combination of the two apertures, contrasts of 2000:1 can be achieved but with a brightness loss approaching 30%. Further increases can be achieved by further constricting the f/# and contrasts up to 3000:1 are possible but the brightness loss can be very severe, reaching over 50%. This level of light loss is currently unacceptable for DLP cinema applications.

3. COMPARISON TO FILM

DLP cinema represents a technology that can deliver consistent color, brightness, uniformity, and contrast. With effective optical design, the variations in each of these parameters can be limited to no more than 10%. With the aid of electronic correction, color can be controlled down to < 0.5% variation from projector to projector. Thus, each and every digital projector can perform almost identically and can do so repeatedly for every showing of digital content. This level of performance does trade-off brightness to achieve the desired color gamut. The current performance level of DLP cinema is shown in table 1 and is compared to typical theatrical release film. DLP cinema has lower efficiency due to the yellow notching filter and apertures for increasing contrast. The contrast, color gamut, and resolution are also lower than can be achieved by film. However, the advantage is the consistency. Film shows large variations in color, contrast, and resolution. Typically, only the film master achieves the highest performance levels shown in table 1. The theatre release copies have variability in performance and degrade over time due to heating and fading effects produced by the Xe lamps.

Table 1: Comparison between DLP Cinema and Film

	DLP Cinema	**Film[5, 6]**
Brightness	10-12 ft-L up to 15 m screens and 6 kW Xe lamp	10-12 ft-L up to 25 m screens and 6 kW Xe lamp
Projector efficiency	2.0-2.2 Lumens/W	3.3 Lumens/W
Color	0.314, 0.351	Varies
Color gamut	Slightly smaller	Wider
Contrast	1300-1500:1	500-5000:1
Resolution	32 lp/mm (SXGA)	30-50 lp/mm
Artifacts	Minimal	Varies (jitter, weave, scratches, emulsion holes)

4. CONCLUSIONS

DLP cinema is the first digital projection technology to make significant advances in converting the entertainment industry from film to digital. In its current state, DLP cinema has shown that performance can be as good as theatrical release film and can exceed it in repeated showings.

To achieve this level of performance, adequate design and tolerancing must be applied to the optical system to limit light loss and minimize variations in performance.

ACKNOWLEDGEMENTS

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