

CINEMA SCREEN UNIFORMITY MEASUREMENT METHOD

by

Erik Heath Arend

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ABSTRACT

Polarization preserving cinema screens often suffer from non-uniformities within the viewing area. These non-uniformities appear bright or dark relative to the surrounding area and can be very visible to the viewers. The current methods to assess these non-uniformities are often visual and not quantitative. The following presents an image-based process for quantifying the uniformity of cinema screens. By incorporating a known gain profile of the screen sample, this method is able to remove the viewing patterns associated with view angle and return a flat field image showing the non-uniformities. This image-based approach additionally provides higher resolution data in less time than laser-scanning systems built for the same purpose.

CHAPTER 1

Introduction

The polarization preserving screens (silver screens) used in today's 3D cinema environments and screens in general, can suffer from various forms of non-uniformities. These non-uniformities typically show up as brightness changes across the screen. As the technology to fabricate cinema screens continues to progress, the overall screen performance increases and these non-uniformities can become more apparent to the viewer. Thus, the measurement techniques used to quantify the screen performance must also evolve. Historically, the inspection methodologies have been visual or taking basic photographs. These methods can be useful when the properties of the screen are changing slowly. However, if the performance changes rapidly, such as a sudden change in brightness at a seam in the screen, these methods may not be able to accurately quantify the brightness change and therefore lead to improper screen construction.

As such, a more rigorous inspection method must be used to identify and quantify the level of non-uniformities that may exist in the manufacturing process. The following describes an image-based method, developed internally at RealD, which can be used to measure the uniformity of reflective screen material. This measurement process is also capable of higher resolution data in a shorter amount of time compared to laser-scanning systems. The system works by capturing luminance images of the screen sample and incorporating information about the screen properties to generate a map of the screen uniformity. Very few assumptions are made about the screen material being measured and therefore the performance of the screen can be properly assessed in a stable and repeatable way.

CHAPTER 2

Background

The technology used to manufacture polarization preserving cinema screens used for 3D projection has gone relatively unchanged since polarization based 3D systems began to grow and dominate the 3D cinema market starting in 2005. The basic process today is to hang a large piece of vinyl on a frame and use automated equipment to spray a metal-based reflective pigment onto the vinyl. Although it is the standard screen manufacturing method today, this process results in screens that have poor stereo contrast ratio, poor total integrated scatter (TIS), visible texture, and/or "hot spot" on screen.

A new screen technology in development by RealD aims to solve the deficiencies of the standard silver screens. As described by Coleman and Sharp (2013), this new method uses a replication process that directly forms the surface of the screen. Directly forming the surface in this manner allows for a smooth and continuous geometry, and thus allows the screen to have high TIS (90%), stereo contrast ratio greater than 250:1, no visible texture, and no hot spot. All of these properties combine to make a screen that reflects nearly twice the light and more than three times the stereo contrast compared to the current silver screens, thus allowing the screen to seemingly disappear from the viewing experience.

The basis of the screen manufacturing is a roll-to-roll replication process. The process starts with a large roll of a plastic substrate. Using a cylindrical tool, a UV curable resin is cast onto one side of the substrate. The cylindrical tool contains the negative version of the desired microstructure. In this way, the desired surface gets cast onto the base substrate in a continuous process. The roll of film is then aluminized using a roll-to-roll evaporative coating. Additional protective coatings

are also applied to the film. The film first undergoes a pre-slit step to narrow width. The film, still in single roll, needs to be assembled into a screen. A specialized seaming table cuts strips of film off of the main roll, slits the film to the final width, and seams adjacent panels together. This process repeats until the screen has been assembled to the desired size.

The replication tool is the basis of the screen performance. Any irregularities during the fabrication of the tool will be replicated in the film and therefore will show up in the final screen as changes in gain (brightness) visible across the screen as a non-uniformity. These types of uniformity concerns are very different than the random non-uniformities that are introduced by the painting process of typical silver screens. The shape of these irregularities can vary from small-localized defects to a gradual change in the gain profile that extends across the entire tool. These gradual (or sometimes not very gradual) changes can occur in both the down web (machine direction) and cross web directions. Due to the roll to roll casting process, these irregularities will also repeat at each revolution of the tool. In this case, the small localized non-uniformities will show up as spots across the entire screen. A cross web slope in the gain profile, "wedge shape", to the uniformity profile can be the most problematic for screen construction. When visually inspecting a single piece of film, the film may appear uniform due to its gradual change in brightness. It is only when two pieces of film are seamed together that the ramp in brightness can be seen due to a large brightness jump at a seam between two panels. The manufacturing steps involved to get to seamed screen can be lengthy and costly. Therefore, it is beneficial to be able to locate and quantify the uniformity at the earliest stage possible.

CHAPTER 3

Overview of Method

When projecting light onto a screen or sample of screen, the brightness, denoted $B(x, y)$ and units of lm/m^2sr , seen by the viewer can be described by the combination of three factors. The first is the illumination profile coming from the projector, denoted as $P(x, y)$. The second is the gain profile of the screen, denoted as $G(\theta_i, \phi_i, \theta_v, \phi_v, x, y)$. This term is a ratio of the bidirectional reflectance distribution function (BRDF), denoted f_r , of the material and a reference sample and is therefore unit less. It is dependent on the incident angles (θ_i and ϕ_i), the viewing angles (θ_v and ϕ_v), and the spatial location on the screen (x, y). It is assumed in this situation that the change in the BRDF is dependent on the spatial location and not the incident or view angles. Thus making the following assumption:

$$\frac{df_r}{dx}, \frac{df_r}{dy} \gg \frac{df_r}{d\phi_{i,v}}, \frac{df_r}{d\theta_{i,v}} \quad (3.1)$$

This assumption is valid for screens at near normal incidence and view angles, and thus at the peak of the BRDF curve. Making this assumption then allows for a spatial uniformity term to be separated out from the gain term, denoted as $U(x, y)$. For an ideal screen, the uniformity function would be unity and therefore does not contribute to the observed brightness. These three factors combine according to equation 3.2. Each of these factors is describing the brightness or change in brightness in terms of the spatial location, in x and y coordinates, on the screen surface. This also assumes the viewer is fixed. Each of these functions will change as the location, relative to the screen surface, of both the projector and viewer, are changed.

$$B(x, y) = P(x, y)G(\theta_i, \phi_i, \theta_v, \phi_v)U(x, y) \quad (3.2)$$

Solving for the Uniformity function then results in equation 3.3.

$$U(x, y) = \frac{B(x, y)}{G(x, y)P(x, y)} \quad (3.3)$$

Therefore, calculating the uniformity of the screen requires knowledge of the brightness seen by the viewer, the gain profile, and the projector illumination profile.

This method describes in detail the process needed to determine each of these factors. The overall brightness function, $B(x, y)$ is captured using a calibrated imaging photometer. The camera, in this case, represents the viewer, and thus the spatial coordinates are represented by pixels in the image. The gain profile, $G(\theta_i, \phi_i, \theta_v, \phi_v)$ is measured on a small representative sample using a goniometer based BRDF measurement tool. Using this information, the gain profile is then expanded into a gain map based upon the projector location and the viewing location. The projector profile, $P(x, y)$ in units of lm/m^2sr , is calculated by using a flat white reference sample in place of the screen sample. For this term, it is assumed that the reference sample is uniform ($U_{ref}(x, y) = 1$) and has a known gain profile close to 1 ($G_{paper}(\theta, \phi) \approx 1$). With all of the raw data collected, each data set is then processed in such a way to ensure they are all in the same coordinate space and a pixel by pixel calculation can be performed resulting in the a final map of the screen uniformity.

CHAPTER 4

Measurement Setup

In order to assess the uniformity of the base screen material, two sets of measurements need to be taken of the film. The first data set is a localized gain curve. The second is an image of a large screen sample when illuminated by a cinema projector.

4.1 BRDF Goniometer

The localized gain curve is measured with a goniometer based system measures the BRDF of the sample. The BRDF of a sample is described by the ratio of the reflected radiance to the incident irradiance. The BRDF can also be written in terms of the power and geometry factors. These relationships are given in equation 4.1.

$$f_r = \frac{L_r}{E_i} = \frac{P_r/\Omega A \cos \theta}{P_i/A} \quad (4.1)$$

This system resembles the bidirectional scatter distribution function scatterometer described by Stover (2012). A green laser is incident on a stationary sample. A swing arm with a detector rotates around the sample and measures the amount of light at each angle. The system is capable of scanning an angular range of $\theta = -84^\circ$ to $\theta = 84^\circ$. Because the detector blocks the incident light, angles between $\theta = -6^\circ$ and $\theta = 6^\circ$ are not collected. A diagram of this setup is shown in Figure 4.1. This system only scans in a single arc, and therefore only captures a small amount of the entire BRDF function at a time. The sample must be rotated around the optical axis (defined by the axis of the laser) and remeasured in order to obtain a full hemisphere of data. For the purposes of this testing, data is only collected at $\phi = 0^\circ$ and $\phi = 90^\circ$. In order to measure the peak of the gain curve, which occurs at the

specular reflection angle, the sample is rotated to 5° around the Ω axis. This places the specular angle at $\theta = -10^\circ$ (in machine coordinates). A diagram of this setup is shown in Figure 4.1.

The gain curve of the material is not a direct measurement. As mentioned before, the gain of the material is relative to a reference screen that scatters light equally in all directions and appears equally bright from all directions. This screen would have a radiance of $L = 1/\pi(sr^{-1})$ and is commonly referred to as a Lambertian Diffuser. For each gain curve, measurements of two samples must be collected. The first is the screen sample itself, including both parallel and crossed polarizers. The second measurement is a piece of the reference screen. For this testing, Spectralon® is used as the lambertian reference sample. The equation for screen gain in a 3D viewing environment is given by 4.2. The BRDF of the screen in the crossed polarization state is not included in this equation because it is blocked by the eyewear worn by the viewer and thus does not contribute to observed brightness.

$$G(\theta) = \frac{BRDF_{Screen\parallel}(\theta)}{BRDF_{Lambertian\parallel}(\theta) + BRDF_{Lambertian\perp}(\theta)} \quad (4.2)$$

All the measurements included in this equation make use of the same geometry, solid angle, detector area, sample area, etc. Therefore the geometry terms in the BRDF equation drop out and the result is the reflected power measured by the detector as shown in equation 4.3. The output product is a gain vs angle curve similar to the one shown in Figure 4.2.

$$G(\theta) = \frac{P_{Screen\parallel}(\theta)}{P_{Lambertian\parallel}(\theta) + P_{Lambertian\perp}(\theta)} \quad (4.3)$$

Additionally, by placing the appropriate polarizers in the incident beam and at the detector, the system is also capable of measuring contrast ratio as a function of angle. Both linear and circular polarization contrast ratios can be measured. This is achieved by measuring the sample first with parallel polarizers and then again

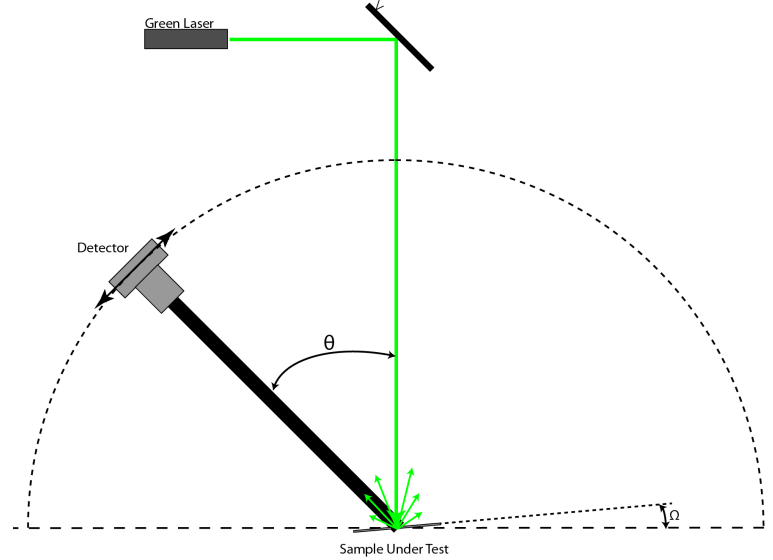


Figure 4.1: BRDF Goniometer

with crossed polarizers. The contrast ratio of the screen is then given in equation 4.4. Again, since these measurements use the same geometry, these terms can be removed from the calculation and only the reflected powers for each sample are required.

$$SCR(\theta) = \frac{BRDF_{\parallel}(\theta)}{BRDF_{\perp}(\theta)} = \frac{P_{\parallel}(\theta)}{P_{\perp}(\theta)} \quad (4.4)$$

4.2 Projector & Camera

The second measurement system captures data from a large piece of screen material. The large screen sample is placed vertically on a vacuum wall. This holds the sample flat with no deformations at the edges. Any mechanical deformations in the film will show up as a non-uniformity in the final result and therefore needs to be removed from the setup. The vacuum wall is capable of holding a sample 38 inches wide and 90 inches tall. This corresponds to the full width of the raw film and 2-3 revolutions of the casting tool.

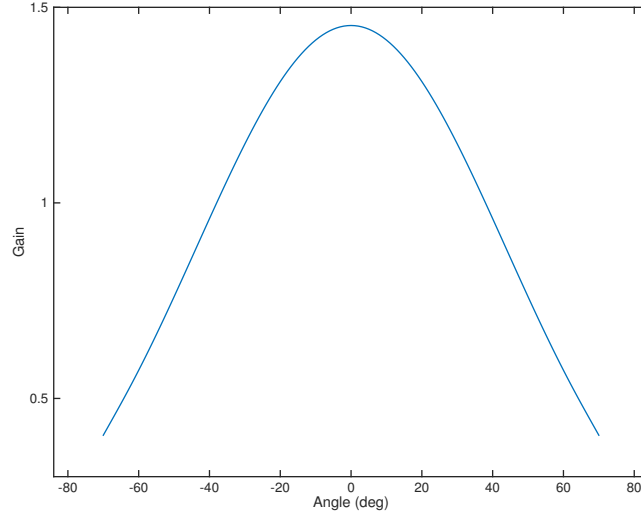


Figure 4.2: Example Gain Curve

A cinema projector provides the illumination for this measurement setup. The projection lens is centered horizontally and vertically to the center of the vacuum wall. The projector is placed 11.25m away from the vacuum wall. At this distance, the vertical dimension of the screen sample subtends an angle of approximately $\pm 10^\circ$. A full white test pattern from the projector is displayed on the screen sample. A slight amount of defocus is added to provide a slight blur of the pixels at the screen. This helps to eliminate moiré between the projector pixels and the camera pixels. Furthermore, the projected image is zoomed down and cropped so that only the screen sample is being illuminated. This minimizes the amount of stray light in the room that can reflect back onto the screen. Both the projector and the vacuum wall are fixed in place and do not move. This provides a stable and consistent platform to measure the geometry of the setup. The geometry plays a key role in the processing of the data and must be known very well. Additionally, the cinema projector is a good platform to use for illumination because the light output is very stable. The high powered xenon lamps provide a very bright image, on the order of 40 footLamberts (fL) in this setup, that is stable to 1% RMS (Donohue and Fernandes,

2004) over the span of several hours. This allows the testing to be completed over the course of 1-2 hours without the need to recalibrate the light levels. However, over longer periods of time, the xenon lamps do degrade. A typical lamp will last between 1000-2000 hours. For this reason, a new calibration image is required at the start of testing each day.

The third component to this system is a camera. The camera is mounted on a tripod and can be placed anywhere in the room. This allows the freedom to capture data at a variety of angles and distances if required, as long as the assumptions in equation 3.1 are still valid. For our testing, the most common camera location is right at the projector. This gives the best location to replicate the uniformity of the screen on axis and at ‘infinity’. When placed at the projector, the camera resolution and field of view equates to a resolution of 5mm per pixel at the screen sample. A diagram of this setup with the camera at a viewing angle of 30° is shown in Figure 4.3.

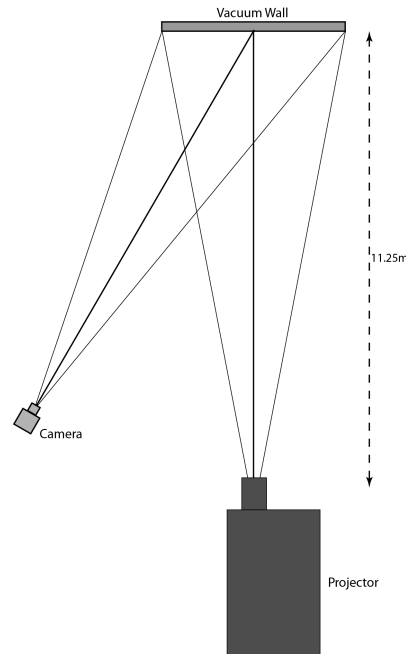


Figure 4.3: Projection and Capture Setup

The camera used for these images is an off the shelf calibrated imaging photometer from Westboro Photonics. The camera sensor is a black and white, 2MP sensor with a photopic filter placed on top. The filter shapes the spectrum in order to provide luminance data. This allows the camera to return a luminance value for each pixel instead of digital counts. The camera also has a high dynamic range, ranging from $0.06\text{cd}/\text{m}^2$ to $100,000\text{cd}/\text{m}^2$, within a single measurement. This is accomplished by electronic bracketing within the software. The system takes images over a range of exposures and then on a pixel-by-pixel basis, chooses the appropriate image from the different exposures to pull from in the final luminance image. The exact details of how this decision is made are proprietary within the manufacturers software. The camera captures images at exposures ranging from 2 milliseconds to 8 seconds. When capturing the image, the software also captures 10 images at each exposure level and then averages those prior to creating the luminance image. This allows any small temporal fluctuations in the projector illumination to be averaged out and produces far more reliable data. In the end, approximately 100 images are used to create the final luminance image.

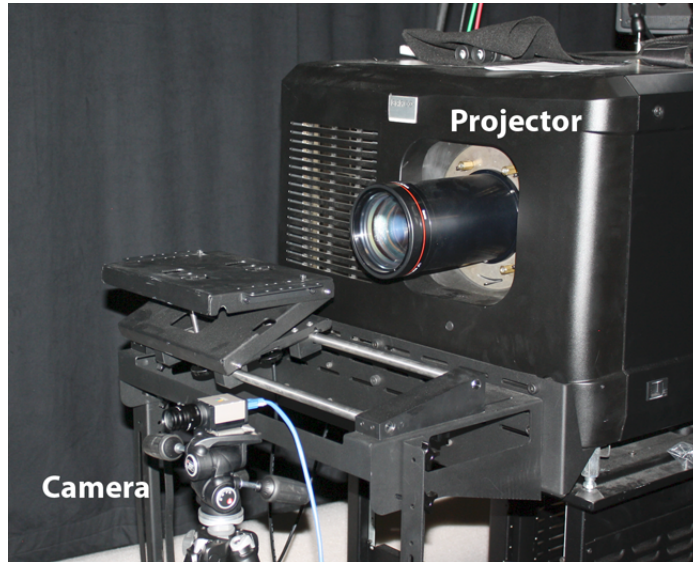


Figure 4.4: Photo of Projector and Camera Setup



Figure 4.5: Photo of Lab Setup. Projector is on the left and Vacuum Wall is on the right

When capturing the images of the screen sample, at least two luminance images are needed for each camera position. The first is a calibration image used to collect information about the physical setup and the projector. Similar to the gain calculation, I use a uniform white diffuser for this. The sample material must cover the same area on the vacuum wall as the screen sample. This large size of diffuser means that a Spectralon sample is not feasible and bright white copy paper is used in its place. Individual pieces of the white paper are placed on the vacuum wall until the entire area is full. This measurement of white paper provides information about the projector brightness and the projector illumination profile. It should be noted that the gain profile of this white paper is also measured using the BRDF goniometer. This allows for a secondary reference back to the primary Spectralon reference. This information is required in the data processing steps to remove the contributions of the projector to the uniformity of the screen sample. The second image is of the screen sample itself. If data from multiple viewing angles are required, a tripod is setup at each location in advance. This allows the samples on the vacuum wall to stay in the same position while the camera is moved to each individual tripod to capture the required images.



Figure 4.6: Photo of Vacuum Wall

4.3 Reference Measurement System

A third measurement system used in this analysis is a reference system. This system was designed and built to handle large pieces of screen material and resembles a large laser scanner. This system can only accept film that is 1.2m long, which is about one-third less in size than the vacuum wall described above. In this system, a large platform scans in X and Y underneath a green laser. The laser is incident on the material at approximately 5° . A detector is placed at the specular reflection angle (-5°). This captures the reflectivity of the sample at near normal. Over the course of approximately eight hours, the platform scans the entire sample at 1cm resolution. The result of this is an XY map of reflectivity over the entire sample.

CHAPTER 5

Data Processing Algorithm

5.1 Processing Method for Image Based Method

With all of the data sets collected, the next step is to pull the relevant information from each set and return a uniformity map of the screen material. There are four main steps to this process. 1. Crop each image to the region of interest, 2. Calculate and remove the projector illumination, 3. Determine the angle from the specular for each pixel in the images, 4. Generate a gain map, 5. Remove the gain map from the data.

The luminance map of the screen sample is referred to as the raw data. This also represents $B(x, y)$ in equation 3.3.

The first step is to determine the cropping region for the images. The sample of screen material is the limiting element in all of the captured images, so the edges of the screen sample will dictate the cropping region and any necessary rotations. Since the camera remained stationary for each image, the region defined by the screen sample will be used for all images.

Even though the projector and camera are fixed for a particular set of images, each point on the screen has a unique angle of incidence and viewing angle. Using the geometry of the projector and camera placement, we can calculate the view angle relative to the specular angle of reflection for each pixel in the images. First a basic coordinate system is setup such that the screen center is at location $(0,0,0)$. The camera and the projector point in the $+z$ direction. This allows for each component to be assigned a coordinate in space and directional vectors to be defined. The normal vector of the screen is also required, which in this case is $(0,0,+1)$ for every

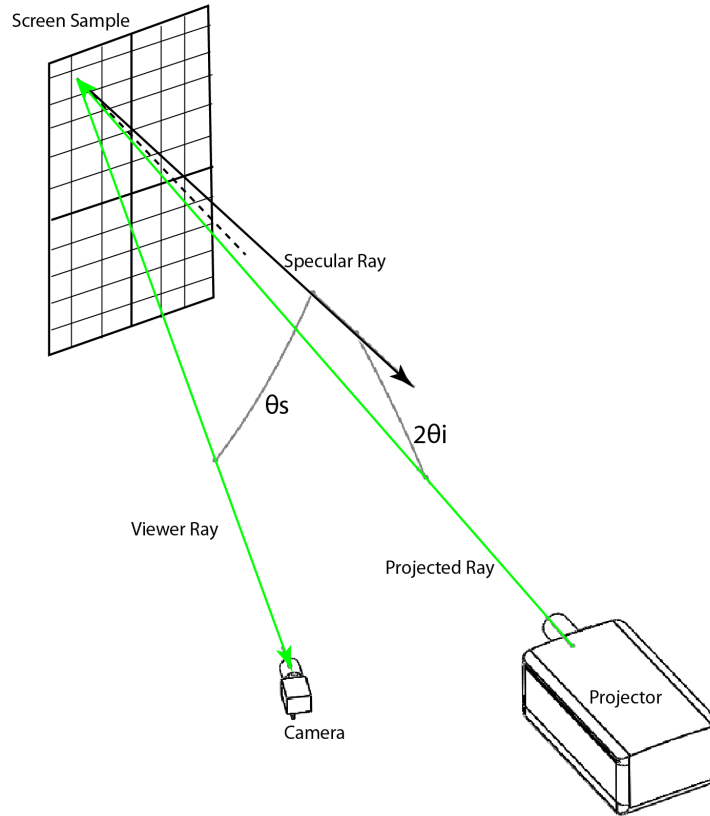


Figure 5.1: Geometry of the Projected and Viewer Rays

location on the screen. Refer to figure 5.1. Using the screen normal vector (dashed line) and the projected ray, a vector that corresponds to the specular reflection is calculated for every pixel in the image. The angle between the projected ray and the specular ray is denoted θ_i . These vectors are then used with the camera location to calculate the angle the viewer ray makes relative to the specular reflection angle, θ_s . This is repeated for every location on the screen (in essence every pixel in the image) to create a map of angles relative to the specular reflection. The result of this calculation is shown in Figure 5.2.

The next step is to determine the projector illumination profile. In terms of equation 3.3, this processing step determines the value of $P(x, y)$ based on a combi-

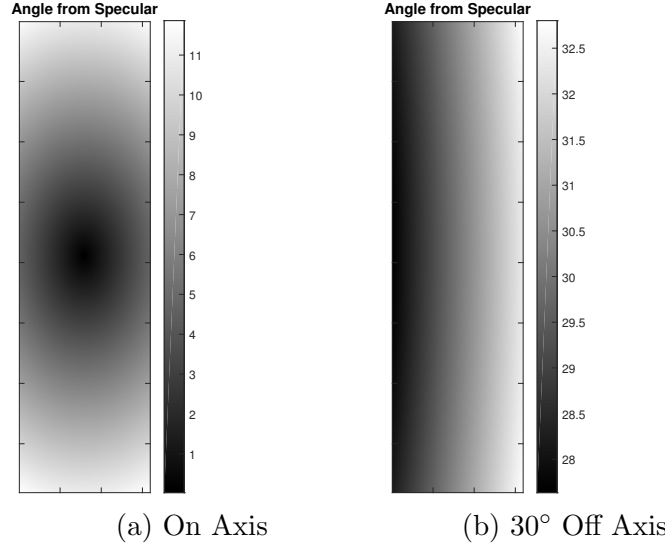


Figure 5.2: Map of Angles from the Specular Reflection for each pixel in the image.

nation of two calculations. The first is to remove the gain profile of the white paper used in the reference image. The gain curve of the white paper, as measured on the goniometer, is used as a lookup table. For each pixel in the map of angles from the specular direction, a relative illumination value is selected from the gain curve. This generates a map of the paper’s contribution to the luminance in the reference image. This map is divided out from the white reference sample image. We are now left with the projector illumination profile. As shown in Figure 5.3a, the image of the white reference sample has gaps between the individual pieces of paper and must be filtered out. A wide gaussian filter (relative to the size of the paper gaps) is passed over the image. The filter has a width of 50pixels and a FWHM of 120px. This filter removes the spikes in the data from the paper gaps but maintains the profile of the projector illumination. Figure 5.3b shows the reference image and the projector illumination profile. The illumination profile is then divided out of the raw screen data pixel by pixel. The result of this division is shown in Figure 5.5b.

The next step is to remove the gain profile of the material from the data. This gain profile represents $G(\theta_i, \phi_i, \theta_v, \phi_v)$ in equation 3.3. Again, using the map of

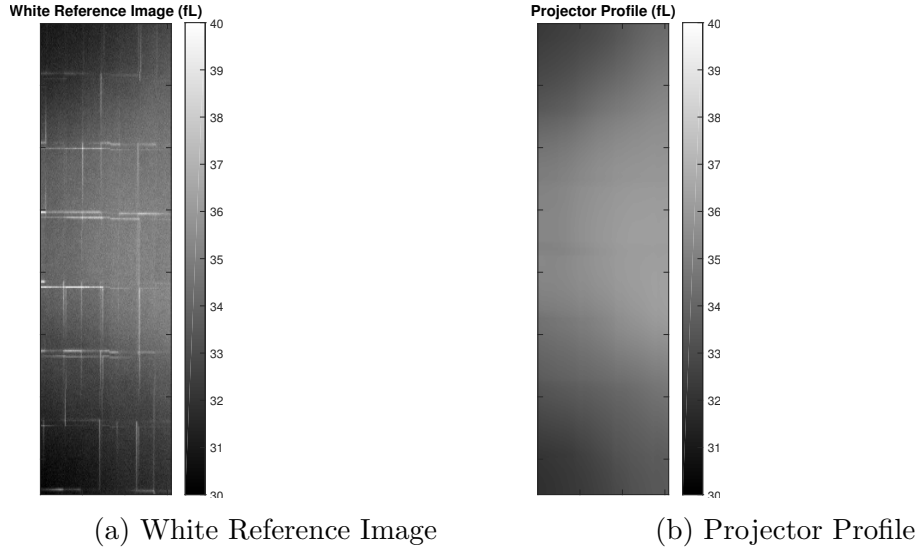


Figure 5.3

angles generated in a previous step, we interpolate the gain curve measured by the goniometer for each point in the map of angles. This generates a gain map (shown in Figure 5.4). This also represents the situation where the screen sample is perfectly uniform. This map is now divided from the screen sample data, thus resulting in $U(x, y)$. The data at this point is also normalized to the mean to provide a percent uniformity. The final result of the processing is a uniformity map as shown in Figure 5.5c. The red areas indicate sections of the screen that are higher than the average brightness. The blue areas represent areas of the screen that are lower than the average brightness. In a perfectly uniform situation, this map would be a single color or a single shade of gray.

5.2 Processing Method For Reference Systems

The data for the reference system is far easier to process. The data is stored in a single file that contains the X and Y values for each location in mm. For each combination of X and Y, a reflectivity value of the material recorded. This data

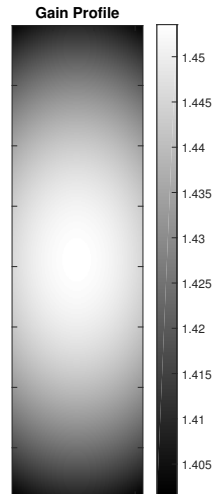
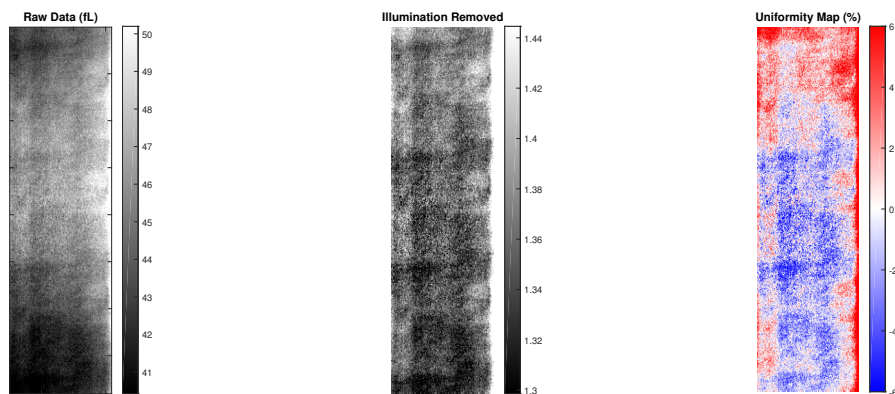


Figure 5.4: Gain Map of Screen Sample



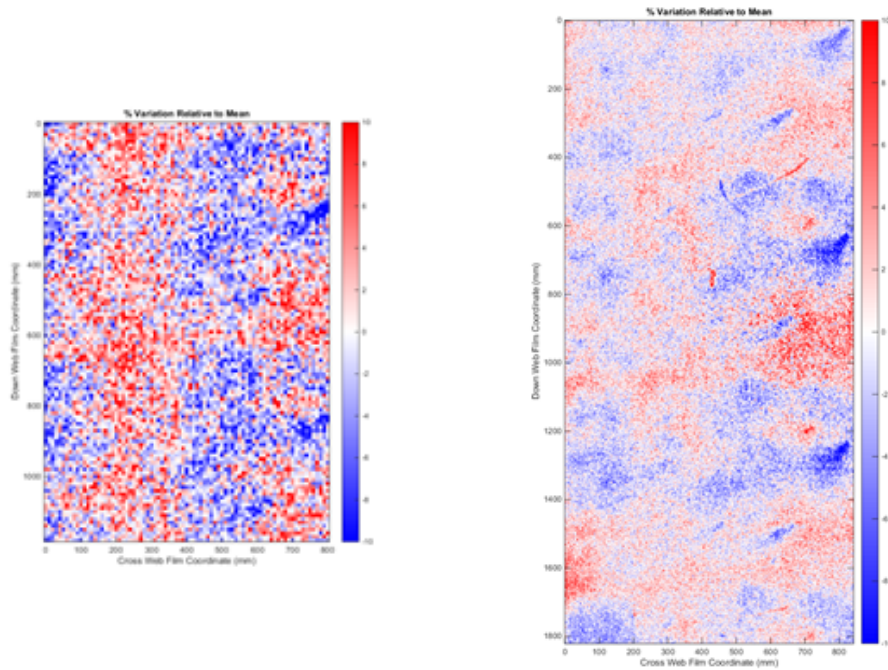
(a) Raw Data

(b) Removing the projector illumination profile

(c) Uniformity Map of Screen Sample

Figure 5.5: Data Processing Sequence

is the direct uniformity of the material and thus no additional factors need to be removed from the data. An average reflectivity is calculated and then the data is normalized to this average, thus resulting in the percent uniformity. This is shown in Figure 5.6a. As a comparison, the same material has been measured with the image-based approach. This data is shown in Figure 5.6b. These two figures are scaled the same and indicate a nearly identical match of each other. The repeating



(a) Data from Reference Systems (b) Data from Image Based Approach

Figure 5.6: Comparison to Reference System

dark blue features on the right side that show up in figure 5.6a also show up on the right side of figure 5.6b. The vertical band near the left side is present in both figures, but in figure 5.6b, there is more detail from the higher resolution data. This provides validation that the image based approach is capable of assessing the uniformity of a screen sample.

CHAPTER 6

Results

With all of the image processing completed on the raw data, the information can be used in a variety of ways to provide guidance about the overall shape of the gain changes, the best regions for uniformity, any defects and their locations.

The image of uniformity is very useful in itself. A quick visual inspection can highlight areas of concern. In Figure 6.1, a localized and repeating defect is seen in the right region of the image. This particular defect is dark and looks like a comet around the $X=650\text{mm}$ location. This defect also repeats at the $Y=300\text{mm}$, 900mm , and 1500mm . Therefore it can be concluded that this defect is inherent in the casting tool. This results in an immediate rejection of the material and the tool.

However, sometimes the average uniformity of the image is needed. In this instance, the average horizontal profile and the average vertical profile of the sample are determined, as shown in Figure 6.2. These plots are quite useful to be able to match the subtleties of the profiles to the image itself. This can help to confirm that features in the profiles do match the features in the image. In the case of this data set, a dark horizontal line on the left side of the screen panel is shown. Also seen are some alternating bright and dark sections at about $X=500\text{mm}$ position. These down web features may show up as a checkerboard pattern if this material were to be made into a full sized screen. Further inspection of the horizontal profile also indicates that the region between $X=200\text{mm}$ and $X=550\text{mm}$ may be suitable for a final screen. The profile shows approximately the same brightness at these locations, therefore there would no perceivable gain step at the seam.

In another example, Figure 6.3 shows some bright and dark vertical bands. These bands are quantified in the horizontal cross section. However, the other aspect to note

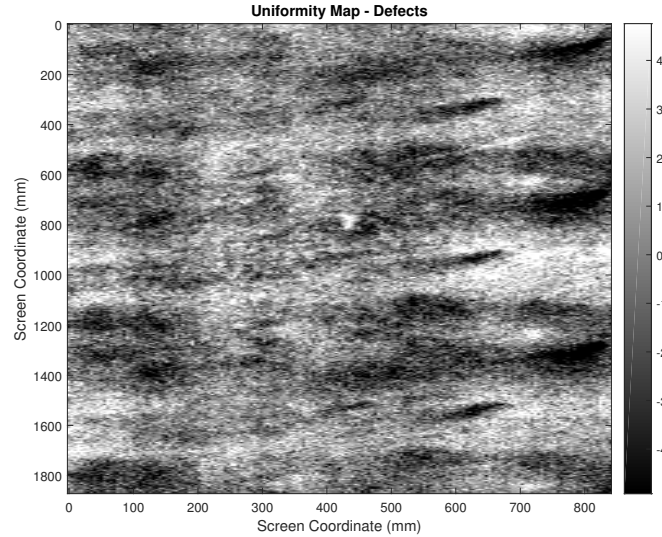


Figure 6.1: Example of Localized Defect

on this sample is the down web uniformity, or vertical cross section as shown. This material would show no signs of a checkerboard pattern.

These images are used as the initial evaluation of the material. If the single panel data looks promising, the data is used to mimic the screen construction method as described in the introduction. Some features in the single panel data may not become apparent until they are repeated with multiple panels seamed together. For this reason, we can take the single panel data and stitch it together to form a virtual screen. Using the data similar to Figure 6.2, we can make the virtual screen shown in Figure 6.4.

With the data, a region of the single panel is chosen to build a final screen. This provides a method to examine repeating patterns on the screen along with the potential gain step when two panels are seamed together. With a quick change of the usable area, we can see what the impact to the final is determined. It would normally take about 1-2 weeks of trial and error in screen assembly to gather this data. The uniformity data used in Figure 6.4 was chosen to highlight that gain step that can occur at a seam. Now that very good data on the screen uniformity is

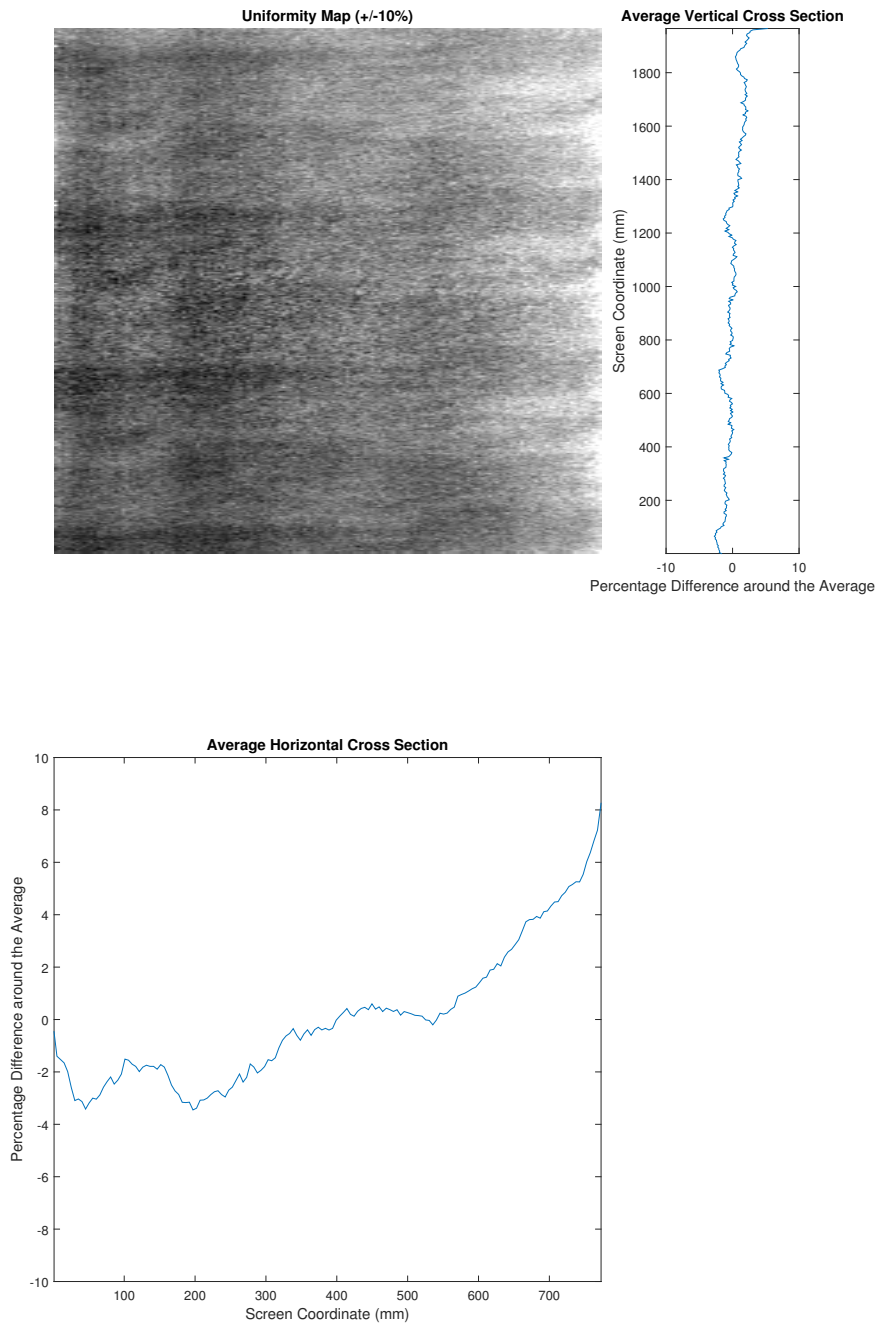


Figure 6.2: Average Horizontal and Vertical Profile

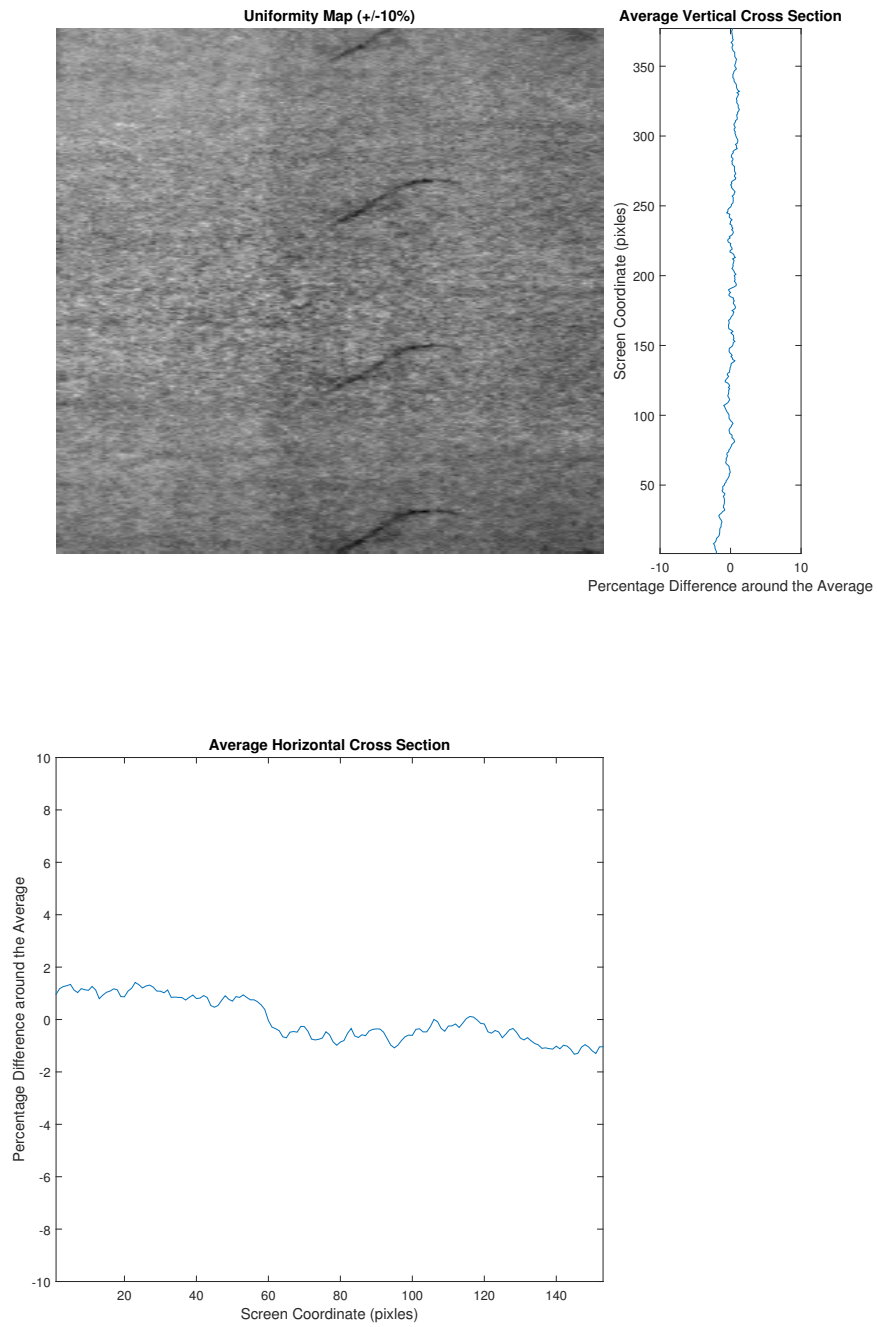


Figure 6.3: Example of Good Down Web Uniformity

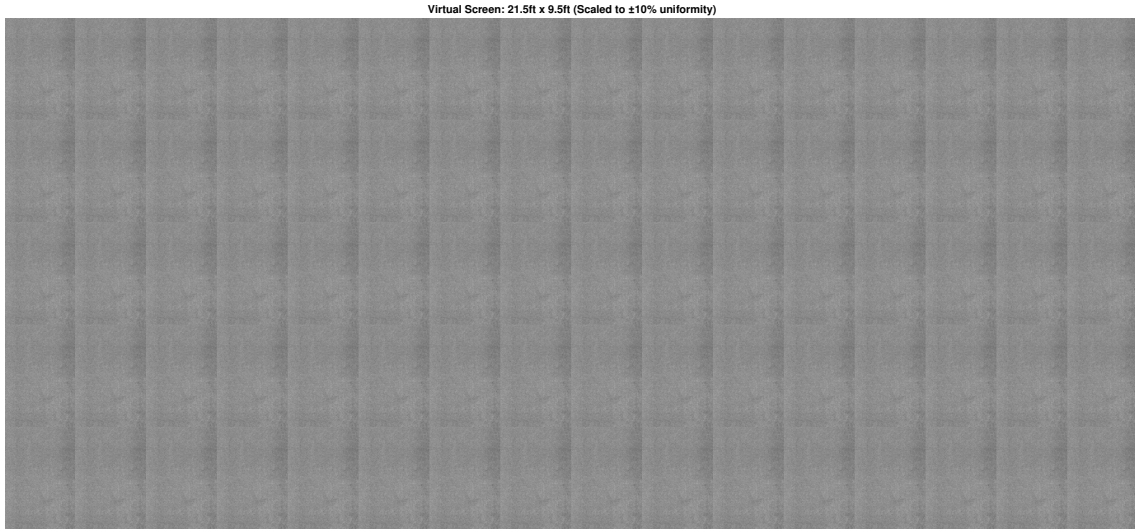


Figure 6.4: Example of a Virtual Screen

available, this quick simulation process is a main contributor to the final instructions for how to build a screen. Taking this a step further and projecting this simulated pattern at real size will provide an even better idea of what features the eye can pick up on the screen.

Having these uniformity maps allows for a variety of analysis options. While only a couple of options are presented here, new ways to use the data is being discovered. Another possible option is to combine on axis and off-axis uniformity maps to fully simulate how a very large cinema screen might appear to the viewer. In this case, the screen often fills the viewer's field of view, such as at a premium large format theater, and a single on-axis analysis does not provide all the necessary information to adequately simulate the screen performance.

CHAPTER 7

Summary

This method of determining the uniformity of a small section of a cinema screen allows for a data driven and quantifiable evaluation process that provides the necessary instructions for the construction of a uniform screen. This method is tied directly to the required specifications of the final product in the fact that it can prove if a new sample of material meets the requirements or can even drive the requirements by quantifying what is pleasing to the eye. It is capable of this while even reducing the cycle time required to gather the data. The data collected with this method drives the decisions of what a good piece of screen material is and what region of the replication tool should be used in the final screen assembly.

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