DOME II: A Parallelized BTF Acquisition System

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Abstract

Bidirectional Texture Functions (BTFs) provide a realistic depiction of the appearance of many real-world materials as they contain the spatially varying light scattering behavior of the material surface. Since editing of existing BTF data is still in its early stages, materials have to be measured from real-world samples. In contrast to the related Spatially Varying BRDFs (SVBRDFs), the reflectance information encoded in a BTF also includes non-local scattering effects and therefore does not obey energy conservation or reciprocity. While this higher degree of freedom also contributes to an increased realism, it inadvertently calls for an extensive measurement of reflectance samples, as many regularization approaches from BRDF measurement do not apply. In this paper, we present an automated, parallelized, robust, fast and transportable setup for the acquisition of BTFs from flat samples as well as 3D objects using camera and light arrays: the DOME II. In contrast to previous camera array approaches, the present setup, which is comprised of high-quality industry grade components, overcomes several issues regarding stability, reliability and precision. It achieves a well balanced state-of-the-art acquisition performance in terms of speed and quality at reasonable costs.

1. Introduction

The accurate digital reproduction of surface material appearance is of great importance in a wide range of applications in industry and cultural heritage, such as product design, virtual prototyping, advertisement and entertainment or the creation of virtual surrogates of valuable objects. The most faithful reproduction of material characteristics can be obtained from measurements of real-world exemplars.

Several acquisition setups have been proposed for this task. They mainly differ in the complexity of the material effects that can be reproduced. The characteristic appearance of a material is the result of light interacting with the surface. While measuring this interaction in its most general case, the 12D Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF), is prohibitively costly, the 6D Bidirectional Texture Function (BTF) lends itself as a realistic approximation. It explicitly includes perceptually important non-local scattering effects, such as shadows, inter-reflections, sub-surface scattering or masking, as an important contribution to a material’s characteristic appearance. As a consequence, BTFs are the technique of choice for the faithful digital reproduction of many real-world materials. The BTF is defined as a function \( \rho(x, \omega_i, \omega_o) \), with \( x \) denoting the position on the surface and \( \omega_i \) and \( \omega_o \) being the light and view direction. A key factor to the realistic impression is the ability to directly render using the acquired data instead of fitted models, given a sufficiently dense sampling.

In this paper, we will present a new hardware design and the necessary calibration and processing procedures for the acquisition of BTFs. Our setup is intended to be widely applicable, which requires a "brute-force" sampling of all 6 dimensions. In addition, we can also robustly and precisely reconstruct 3D geometries. This allows for the dedicated acquisition of mesoscopic material geometry, e.g. displacement maps, as well as capturing shape and reflectance of complete 3D objects. To make our setup practically feasible,
we find a compromise between sampling resolution, measurement quality and speed as well as reliability and costs of the employed hardware.

2. Related Work

A recent detailed overview of setups for capturing material appearance can be found in [HF11]. In the following, we will briefly summarize those approaches most closely related to our designated purpose of measuring BTFs. A more detailed comparison can be found presented in the appendix.

Gonioreflectometer Setups: In the first BTF measurement device proposed in [DNVGK97], a flat material sample is mounted on a robotic arm which changes its pose relative to a fixed light source. The sample is captured by a camera being placed at seven different positions during measurement. Due to mechanical constraints and the need for manual interaction, only a sparse set of directions was captured and anisotropy was handled insufficiently. More recent works [SSK03, HFV12] presented automated versions of a similar setup that allow for much higher direction samplings and also account for anisotropy. However, the involvement of moving parts in these setups impacts both accuracy and measurement time. Every single picture has to be carefully calibrated e.g. by using markers next to the material sample.

Kaleidoscopes: In kaleidoscope-based approaches [HP03, IRM*12], a clever arrangement of mirrors provides a set of recursive inter-reflections that present all views to the camera at once. Using a digital projector in combination with a beam-splitter, different light directions can be generated utilizing the same inter-reflection paths as the view directions. Therefore, all parts of the setup remain fixed. Although the light directions still have to be sampled sequentially, view directions and spatial domain are captured in parallel, allowing a considerable speed-up of the measurement compared to gonioreflectometer devices. However, these setups involve a trade-off between spatial resolution and the number of possible direction combinations and require a highly accurate calibration. In [IRM*12], the authors demonstrate that reflectance can be captured from 3D surfaces using this approach.

Camera Arrays: A different way towards reduction of measurement time can be found in using arrays of light sources and cameras. In [MMS*04], a highly-parallelized dome setup with 151 digital consumer cameras mounted on a hemisphere above the material sample is presented. Using this setup, BTFs can be measured without any moving parts. All cameras take pictures at the same time, capturing all view directions in parallel without sacrificing spatial resolution. In [SWRK11], the setup is extended with projectors to facilitate the acquisition of BTFs from 3D surfaces. The approach followed in this paper falls into this category as well. However, our setup has a reduced number of cameras which is compensated by additionally using a rotation stage. A similar trade-off was made by Köhler et al. [KNS13] for capturing the reflectance on 3D objects with a full-spherical arrangement. In contrast to our approach, their setup still requires to move the cameras, which is observed to be an obstacle for a stable calibration.

3. Hardware Design

Our setup consists of a dome structure with industrial digital video cameras, a precision rotation stage and LED lamps. Light-sources and cameras are rigidly aligned and stay at fixed positions during the whole measurement. The rotation stage, which is used for capturing anisotropic materials, is the only movable part. Yet, it is fast, accurate and reliable. In the following, we will provide a more detailed discussion of the individual hardware components.

Gantry: The gantry should meet the following requirements: (i) sufficient space for all components, (ii) a hemispherical structure that facilitates sample size, focus distance and depth-of-field, (iii) stable and rigid mounting of the hardware, (iv) a compact and light-weight construction for being transportable, (v) being openable for maintenance access, and (vi) allowing the installation of an automatic feed for samples. Our setup, illustrated in Figure 1, meets these requirements by a dismountable, light-weight hemispherical structure. The diameter of 2m provides a sufficient distance to the material samples. The hemisphere is organized in rings at inclination angles \(\theta = 0°, 7.5°, ..., 90°\) on which cameras, LEDs and projectors are installed and which are held in place by struts. There is enough space to let an automatic feed pass through below the ring at 90° inclination.

Cameras: We use eleven cameras that are mounted on an arc above the material sample at different inclination angles \(\theta_o = 0°, 7.5°, ..., 75°\). When turning the rotation stage in steps of 15° to different azimuth angles \(\phi_o\), we are able to sample the view directions \(\omega_o = (\theta_o, \phi_o)\) in a dense, regular grid of \(11 \times 24\) with some degree of parallelism.

We employ SVS Vistek SVCam CF 4022COGE cameras (CCD-sensor with CFA, 2048 \(\times\) 2048 pixels, 12bit/pixel, 8FPS). The large sensor (16 \(\times\) 16mm) provides for a high light sensitivity at low noise levels. To account for the high dynamic ranges (HDR) found in material reflectance, the electronic shutter has customizable exposure times from 50\(\mu_s\) to \(\infty\). The raw-data is transmitted via Gigabit-Ethernet, which also serves as the control-connection. All eleven cameras are operated by a single computer, avoiding any synchronization issues or the fragmented storage of the measured data. We sample the BTF at three spectral bands (RGB), given by the Bayer color-filter-array (CFA) of the camera.

The cameras are equipped with high-quality ZEISS Makro Planar T*2 ZF=1 prime lenses. A set of lenses...
with 100 mm focal length is employed for measuring BTFs from flat material samples, offering about 380 DPI spatial resolution. For measuring BTFs on larger 3D objects, a second set with 50 mm is available. We use a fixed aperture of f/19 on all lenses to have a sufficiently large depth of field and focus on the center of the DOME II. Both settings are fixated using locating screws, which vastly improves stability of calibration throughout multiple measurements.

**Light Sources:** For sampling the light directions \( \omega_i = (\theta_i, \phi_i) \), we equipped the full hemispherical gantry with a light dome of individually switchable LED lamps. This avoids the use of movable parts for the light sources.

188 LEDs are placed evenly spaced on the rings at 0° to 75° inclination. Care has been taken that the positions are in alignment under rotations \( \phi_i \) in increments of 15°, also leading to a regular grid of 11 × 24 light directions. To facilitate the usage of Helmholtz reciprocity for 3D reconstruction (see for example [WRO+12]), the lights are arranged symmetrically around the cameras and thus allow the formation of reciprocal pairs for rotations of \( \pm 15° \pm 7.5° \). Another 10 light sources are arranged to emit into the perfect reflection direction of the cameras at 7.5° to 75°, allowing a better observation of specular effects.

We selected Barthelme Bari DC show-case LED lamps (2.5 W, 215 lm, phosphor coated, 6000 K) which emit a broad spectrum, matching the cameras’ CFAs, and come with optics to concentrate the light on a single spot, i.e. the material sample. All LEDs are from one batch to avoid differences in brightness and spectra. Additionally, after switching on an LED we wait for it to reach a stable operating conditions and thus reproducible characteristics.

**Projectors:** To facilitate the measurement of BTFs on 3D objects instead of planar samples, the Dome II setup is equipped with four LG HS200G digital projectors (800 × 600 pixels, LED-DLP, 200 lm) for reconstructing the 3D geometry via structured light. The projectors are installed next to the camera arc at different inclination angles from 0° to 90°. They are small, light-weight and have a sufficiently near projection distance and wide depth of field for our use-case.

We observed that after turning on, the projection drifts and takes up to 15 minutes to stabilize. Additionally, the colors alternate periodically with a slightly irregular pattern, making it necessary to synchronize exposure with projector frequency in order to avoid color shifts. Due to these shortcomings, we plan to replace the projectors with CASIO XJ-A141 (1024 × 768 pixels, LED-DLP, 2500 lm). In our first experiments, these models did not exhibit a drift and also facilitated shorter synchronization times.

**Turntable & Sampleholder:** The sample is fixated by a blackened sampleholder (Fig. 2e) and placed on a Newport URS-150BCC computer controlled precision rotation stage with a guaranteed uni-directional repeatability of 0.002°. The detachable sampleholder is held in place by four register pins (Fig. 2d). A cover plate with additional registration markers is put on top of the material sample and provides an adjustable clamping pressure via four screws. The visible area of the material sample is 7.5 × 7.5 cm. 3D objects are placed on the sampleholder without the cover plate, which requires a precise calibration of the device.

![Diagram of DOME II components](image)

**Figure 2:** The custom-tailored calibration targets (a) and (b), the sampleholder (c) and the fixation mechanism (d).

4. Calibration, Measurement & Processing

One advantage of the proposed setup is the fact that all parts, except the sampleholder and turntable, are rigidly affixed to each other. Still, since the turntable shows a high accuracy and the sampleholder is held in place without mechanical play, we also consider their positions reliable. This allows to perform one thorough calibration that is then used for several measurements.

**Calibration:** The geometric calibration of all parts is performed utilizing a custom-tailored target (Fig. 2a) that features a 10 × 10 cm plate with 484 fiducial markers [MS13] and four polished bearing balls. Markers and balls have a known size and position. The target is placed on the turntable instead of the sampleholder and rotated to be captured in various different poses. The cameras are calibrated via the fiducial markers, employing Zhang’s algorithm [Zha00] with a successive sparse bundle adjustment [LA09]. The resulting re-projection errors are 0.16 pixels on average, which corresponds to a spatial error of 11 µm and an angular error of 0.001° in the view direction. The turntable’s axis and center of rotation are obtained from the triangulated 3D locations of the markers. After calibration, different poses are brought into alignment with an average deviation of 0.003°.

For calibrating the light positions, we identify for each light its reflection-point in all four bearing balls. Using these features and a good initial estimate for the bearing balls’ positions and radii, we can compute the reflection rays via ray-tracing and triangulate the LED position from them. Afterwards, we perform a non-linear optimization on all LEDs.
and the sphere positions simultaneously to reduce the re-
projection error of the observed reflections. Here, we can
report an average error of 0.4 px, corresponding to an an-
gular error of about 0.08° for the light directions.

In addition to the geometric calibration, a radiometric cal-
ibration is performed. First, we take a set of dark-frames,
i.e. raw images of a completely unlit scene, with all cam-
eras and at different exposure times. Then, we compute the
cameras’ response functions by taking an exposure series
and employing the method of Robertson [RBS03]. Finally,
a white-frame for every camera and light combination is
captured from a white-target made from SphereOptics
ZENITH UltraWhite (Fig. 2b) that is put in place on the
rotation stage. Our target is almost perfectly lambertian with
an albedo of 99% in the visible spectrum.

Using dark-frame subtraction and the inverse response func-
tion, we eliminate sensor-bias as well as dead- or hot-pixels
and obtain linear values proportional to radiance. Dividing
these values by the values in the corresponding white-frame
we obtain the reflectance \( \rho [sr^{-1}] \) (see appendix).

**Measurement:** We execute our measurement procedure
with the goal to minimize the time spent waiting for slow
operations to finish. Given a planar sample, we first move
the rotation stage to the desired pose. Then we consecu-
tively switch through the light-sources, always illuminating
the sample with exactly one LED, and for each one take a
HDR exposure series with all cameras simultaneously.
Reconstructing 3D geometry, we also perform a structured
light measurement. Here, we first switch on the projector and
then rotate through the desired poses. For every rotation we
capture a 2D pattern sequence with all cameras.

The raw images are captured directly onto a clean hard-
disk to avoid loosing write-speed due to file-system frag-
mentation. Still, depending on the exposure time the data
rate can reach 528 MB/s and the disk’s write-speed becomes
a limiting factor for the measurement performance. There-
fore, we employ a write-queue in RAM which is worked off
during more time-consuming operations.

Depending on the dynamic range of the material, a full
anisotropic BTF measurement takes between 4 and 10 hours.
Additionally acquiring the 3D geometry takes another 1.5
to 3 hours. Instead, capturing a flat isotropic material will
merely take 15 to 30 minutes in total. A more detailed dis-
cussion on measurement times can be found in the appendix.

**Postprocessing:** To allow efficient storage, compression
and rendering, every single HDR image of the captured BTF
data is first rectified by computing and applying the re-
spective projection onto a reference geometry. Convention-
ally, this is a plane, but could also be a heightmap or the
parametrized 3D geometry of an object, which we recon-
struct from the structured light. As a result we obtain 52,272
rectified images. However, for planar materials, \( \theta_y \) and \( \theta_o \)
 vary by about 4.3° over these image. In the case of 3D ob-
jects, the directions in an image are completely arbitrary. For
compression and rendering, an evenly-spaced, dense sam-
ping of the angular domain would be desirable. Therefore,
we perform an angular resampling on the rectified images
employing the method described in [SWRK11].

**5. Conclusion and Future Work**

We have presented a measurement device that is capable of
capturing BTFs densely and unbiased in all six dimensions.
Our setup yields a reasonable compromise between acquisi-
tion speed, processing and calibration effort, costs and qual-
ity as well as general robustness. In contrast to most other
setups, the hardware is constituted from high-quality indus-
ty parts that we selected for reliability and endurance. This
way, our setup is fit to serve as a mass acquisition device for
practical application even outside a lab environment.

Most of the money is spent on the high-quality cameras and
lenses, which make up the heart of an optical measurement
instrument. However, in turn we limit ourselves to eleven
cameras and alleviate the hereby induced issues of speed and
registration by employing a full light-dome, a precision ro-
tation stage and a thorough calibration and post-processing.
As a result, we achieve measurement times that lie in the
middle between the latest dome setups and gonioreflectome-
ters, while at the same time capturing 2.2 or 8 times as many
directions, respectively. The spatial resolution, sample sizes
and 3D abilities are on the state of the art as well. To the
best of our knowledge, our setup is the first of its kind that
is specifically designed to be easily transportable and can be
assembled and calibrated in 16 hours.

As a next step, we plan to extend the setup with an ad-
tional camera and another ring of LEDs to better capture
the important reflection effect predicted by the Fresnel-
equations. Further plans include improving the measurement
speed and calibrating the CIE color-profile of our device for
colorimetric correct material visualization.

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Appendix 1: Problem Definition
Consider the BTF as a function

$$\rho: \mathbb{R}^2 \times \Omega \times \Omega \rightarrow \mathbb{R}^n (x, \omega_i, \omega_o) \rightarrow (\frac{\partial l(x, \omega_i)}{\partial l(x, \omega_o)}),$$ (1)

giving the ratio of the differential incident irradiance $\partial E_i$ from direction $\omega_i$ to the differential outgoing irradiance $\partial L$, at position $x \in \mathbb{R}^2$ on the material sample into direction $\omega_o$, with $\omega_i = (\mathbf{r}, \varphi_i) \in \Omega$ and $\omega_o = (\mathbf{r}, \varphi_o) \in \Omega$ being directions in the hemisphere $\Omega = [0, \frac{\pi}{2}] \times [0, 2\pi]$ above the material sample. The ratio is defined for a set of $n$ discrete wavelength-bands $\lambda_i$. In contrast to a full BSSRDF, the simplifying assumptions are made that $\rho$ does neither show fluorescence nor phosphorescence and that the incoming light from direction $\omega_i$ is the same for all points on the material sample, allowing to account for sub-surface light-transport using only an exit position $x$.

Appendix 2: Radiometric Correction
From the Rendering Equation we get

$$L(x, \omega_o) = \int_\Omega \rho(x, \omega_i, \omega_o) L_i(x, \omega_i) \cos \theta_i d\omega_i.\,$$

Let us consider a specific pixel in the camera’s image. This way, we can assume the outgoing direction $\omega_o$ and the position on the surface $x$ to be constant and dismiss them in our considerations of the image formation process. Then the radiance $L [\text{Wm}^{-2}\text{sr}^{-1}]$ up to a proportionality factor $\alpha$ is obtained from a camera-pixel’s value by subtracting the radiance

$$\alpha L_m = \alpha \int_\Omega \rho L_i(\omega_i) \cos \theta_i d\omega_i \,$$

and $\alpha L_w$ being the measured values in the image taken during measurement and its corresponding white-frame, respectively.

$$\rho = \frac{\alpha L_m}{\alpha L_w} = \frac{\alpha L_m}{\pi \alpha L_w}.\,$$

Thus, we can determine the value of $\rho$ for the fixed sample $(x, \omega_i, \omega_o)$ as follows

$$\rho = \frac{\alpha L_m}{\alpha L_w} = \frac{\alpha L_m}{\pi \alpha L_w}.\,$$

Consider the white-target to be a perfectly lambertian object with known albedo $a$. Then $\rho$ is simply $\frac{a}{\pi}$ [sr$^{-1}$] and $\alpha L_m$ is formed by

$$\alpha L_m = \alpha \int_\Omega \frac{a}{\pi} L_i(\omega_i) \cos \theta_i d\omega_i \,$$

Here, $L_i [\text{Wm}^{-2}\text{sr}^{-1}]$ denotes the (unknown) radiance coming from the scene due to light-source $l$ being switched on.

Furthermore, we know that the irradiance $E_w [\text{Wm}^{-2}]$ at the observed point on the surface must be

$$E_w = \int_\Omega L_i \cos \theta_i d\omega_i \,$$

Now, consider the measurement of an arbitrary unknown reflectance function $\rho(x, \omega_i, \omega_o) [\text{sr}^{-1}]$. Let us further assume that the light illuminating the observed surface point covers only a small solid angle $\omega$ and $\rho$ is constant over $\omega$ for fixed $x$ and $\omega_0$. This assumption is reasonable for a single LED emitter at a large enough, which can be considered to be almost a point light. Then the image formation process leading to measured radiance $\alpha L_m$ for a single camera pixel (constant view direction and point on surface) and single LED (constant reflectance behavior) can be written as

$$\alpha L_m = \alpha \int_\Omega \rho L_i(\omega_i) \cos \theta_i d\omega_i \,$$

$$= \alpha \int_\Omega L_i(\omega_i) \cos \theta_i d\omega_i \,$$

$$= \alpha E_w.\,$$

Appendix 3: Setup Comparisons

<table>
<thead>
<tr>
<th>Paper</th>
<th>Gonioreflectometers</th>
<th>Kaledioscopes</th>
<th>Camera arrays</th>
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<tr>
<td>DOME II</td>
<td>56.25</td>
<td>380</td>
<td>52,272</td>
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</tbody>
</table>

All figures are taken from the cited documents and other publicly available sources, such as websites describing the device. It might be possible that some numbers have been improved since their original publication. The number of actually employed physical cameras is given as a hint to estimate the costs and complexity of a setup.

Appendix 4: Measurement Details
The measurement times and number of captured images depend on the dynamic range of the material and hence the number of required images in an exposure series. Let $\text{Exp}_1, \text{Exp}_2 = E_1$ denote the set of exposure times we take for the BTF measurement and $\text{Exp}_2, \text{Exp}_2 = E_2$ denote the
set of exposure times we take for capturing the structured light patterns.

For measuring a BTF we perform $R_1 = 24$ rotations, in each rotation switch on and off $L = 198$ lights, and capture a HDR exposure series with $E_1$ exposures on all $C = 11$ cameras simultaneously. For measuring a 3D geometry, we switch on and off $P = 4$ projectors, perform $R_2$ rotations, project $N = 42$ patterns and capture an HDR exposure series with $E_2$ exposures on all $C = 11$ cameras simultaneously. Each captured image is $2048 \times 2048$ pixels at 12 Bit (6 MB).

**Files and Filesize:** For BTFs we capture $R_1 \cdot L \cdot C \cdot E_1$ raw images, which constitute $R_1 \cdot L \cdot C = 24 \cdot 198 \cdot 11 = 52,272$ rectified HDR images. Usually, $E_1 = 2 \ldots 4$, thus a raw BTF measurement has between $2 \cdot 52,272 = 104,544$ and $4 \cdot 52,272 = 209,088$ images, occupying 612.6 GB - 1.2 TB of disk space. The full $7.5 \times 7.5 \text{cm}$ at 380 DPI will result in

$$\left( \frac{7.5 \text{ cm}}{380 \text{ DPI}} \right)^2 \cdot 2 \cdot 52,272 \cdot 2 \text{ B} = 122.5 \text{ GB}$$

for the rectified images (in 16 Bit half-precision floating point).

For the structured light images, we choose $R_2$ depending on the geometric complexity. Usually $R_2 = 8$ and $E_2 = 1 \ldots 3$. Thus, we have $R_2 \cdot P \cdot N \cdot C \cdot E_2 = 8 \cdot 4 \cdot 42 \cdot 11 \cdot E_2 = 14,784$ to $44,352$ images, occupying 86.6 GB to 260 GB, from which a 3D geometry is reconstructed (see [WRO+12]).

**Measurement Time:** The total measurement time $T$ can be expressed by three parts: time spent capturing images $T_c$, time spent waiting for hardware operations to finish $T_d$ and the time required to write the images onto the disk $T_h$. Thus

$$T_c = \max (T_c + T_h, T_h)$$

$T_d$ and $T_c + T_h$ can be considered separately, since we employ a write-queue in RAM. $T_h^{\text{BTF}} = \frac{5 \text{ MB} \cdot R_1 \cdot L \cdot C \cdot E_1}{D}$ and $T_h^{3D} = \frac{8 \text{ MB} \cdot R_2 \cdot P \cdot N \cdot C \cdot E_2}{D}$, where $D$ denotes the average disk’s write speed. In most of our measurements, this was about $D = 40 \text{ MB/s}$.

$$T_h^{\text{BTF}} = \sum_{r \in \text{Exp}_r} (t + 3 \cdot 125 \text{ ms}) \cdot R_1 \cdot L \text{ and } T_h^{3D} = \sum_{r \in \text{Exp}_r} (t + 3 \cdot 125 \text{ ms}) \cdot R_2 \cdot P \cdot N.$$ 

To improve the CCD-clearing performance, we actually take 3 images per shot (two with 50 μs and one with the target exposure). Each time we have to wait 125 ms, due to the cameras’ frame-rate of 8 s$^{-1}$. Note that the factor $C$ is not included in the capture-times, since the cameras all capture in parallel.

Finally, $T_h^{\text{BTF}} = R_1 (9 \text{ s} + 250 \text{ ms} \cdot L)$ and $T_h^{3D} = 15 \text{ min} \cdot P + R_2 (9 \text{ s} + 100 \text{ ms} \cdot P \cdot N)$. In both cases we assume that we have to wait 9 s for the turntable to reach its new pose. In the BTF case, we wait a warm-up delay of 250 ms after switching on each light in order for the spectral characteristics to stabilize (see Figure 3). In the 3D acquisition case, we wait 15 min per projector for the projection to stop shifting. As mentioned before, we plan to replace the current projectors with new models, to avoid this unnecessary delay. Additionally, we cautiously wait 100 ms after each change of pattern for the projector to actually display the new one.

![Figure 3: A time series of the spectral power distribution of our LED light-sources. The light-source is turned on at time $t = 0 \text{s}$. Note that higher wavelengths take more time to reach their final power output. The vertical red line at $t = 240 \text{ ms}$ marks the time at which the 99th percentile of the final power is reached. After this point we consider the spectral characteristics to be stable.](image-url)