Signal-to-Noise Ratio Improvement Using Multiplexed Illumination with Scattering Media

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ABSTRACT

Empirical measurement of the attenuation of a light ray (i.e. a laser beam) through a scattering medium is challenging because the radiance of the exiting light is near the noise floor of the detector. The SNR can be improved with multiplexed illumination, where several different rays are sent simultaneously resulting in much higher outgoing radiance. The contribution of an individual ray is determined by solving a linear system. We perform an experiment to determine the empirical improvement in SNR using multiplexed illumination in place of single-ray illumination. The experiment shows that the empirical improvement does not follow the predicted theoretical improvement.

CCS CONCEPTS

• **Computing methodologies → Computational photography**; **Volumetric models**; **Image processing**.

KEYWORDS

multiplexing, multiplexed illumination, noise analysis, scattering, imaging, physics

1 INTRODUCTION

The material properties of a scattering medium can be determined by shining laser beams through the medium and measuring the light's attenuation for various entrance and exit positions and orientations.

But a scattering medium attenuates light rapidly, which creates low-intensity outputs near the noise floor of the detector. This poor single-to-noise ratio leads to poor estimates of the medium's material properties. If the total intensity of photons arriving is below the noise floor, it is said to be *underexposed*, creating dark and noisy regions in the image.

Recently, the problem of reconstructing the materials of scattering media is of importance. It can be used for medical imaging, atmospheric physics, or rendering applications. Different approaches have sought to understand the parameters for a homogeneous medium [1–3] as well as heterogeneous [4]. The latter is of particular interest for reconstructing medical imaging or other physical phenomena. In order to accurately study or reconstruct these phenomena, a suitable SNR (SNR) is required.

To increase the SNR, more light can be added. For scattering media, however, the amount of light needed with a single, brighter source could damage or burn the medium.

Multiplexed illumination is a method by which the medium is illuminated by a large number of laser beams at once. This is repeated many times with different on/off patterns of the lasers [5]. In a standard setup, half of the lasers are on (or active) at a time. An individual laser's contribution can be determined by measuring the output from a sufficient number of these on/off patterns and solving a linear system.

The measurment corresponding to an individual laser – when calculated from multiplexed illumination – has a higher SNR than that corresponding to the same non-multiplexed individual laser.

Hadamard codings are used to generate patterns of multiplexed illumination, and yield following theoretical improvement to the SNR with n_{lights} lasers in total [5]:

$$\frac{\text{SNR}_{\text{Hadamard}}}{\text{SNR}_{\text{single}}} = \frac{\sqrt{n_{\text{lights}}} + \frac{1}{\sqrt{n_{\text{lights}}}}}{2} \approx \frac{\sqrt{n_{\text{lights}}}}{2}. \quad (1)$$

When light from a single laser scatters a medium, the individual photons may reach many boundary positions. With multiplexed illumination, each boundary position of a medium may receive contributions from many, perhaps all, lasers. By multiplexing 64 light sources from an 8×8 grid, for example, the SNR could theoretically be improved by a factor of four.

However, this theoretical improvement does not model underexposed regions. In this paper, we address the issue of underexposure by determining the factor of improvement both for the distances from the centre of a multiplexed array as well as for the depth of a scattering medium.

Increasing illumination is important not only for the signal-to-noise ratio, but also for the capture time. If many different photographs are taken, a faster shutter speed should be used, requiring more light in the scene for constant *ISO* and aperture. A faster shutter speed permits the use of video cameras, including high speed video with alternating images from different polarization angles [6]. Other applications of multiplexing allow us to capture multi-spectral images [7] or to recover scenes by separating direct and global illumination components [8].

Our goal was to measure the signal-to-noise ratio (*SNR*) for multiplexed illumination versus single-source illumination over the whole volume of different scattering media. The SNR$(r_{\text{med}}, d_{\text{med}})$ was measured as a function of the radial distance, r_{med}, from the centre of the medium, and the depth of the medium, d_{med}. The media consisted of different milk/water concentrations at different

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depths. The *SNR* was measured for each concentration to see how scattering (related to concentration) affects the SNR for multiplexed versus single source illumination.

2 APPROACH

The experiment used a multiplexed system of 64 5mW laser diodes in an 8×8 array. The scene was illuminated with different subsets of 64 of these lasers and the Hadamard system of equations was used to determine the contributions of the individual lasers. The experiment was then repeated using *individual* lasers at the same exposure.

The multiplexed laser array was placed under a container filled with a liquid medium, as shown in Figure 1 and Figure 2. A video camera recorded the scene while varying Hadamard codes were used for the multiplexed array. After the codes were exhausted, individual lasers were illuminated, one at a time. The experiment was repeated with increasing amounts of liquid in the container and with different liquids having different scattering properties.

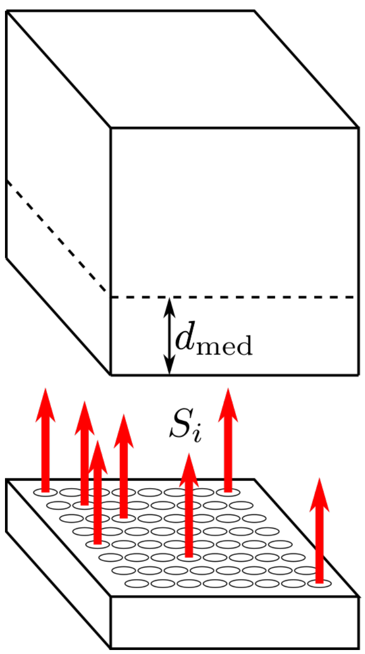


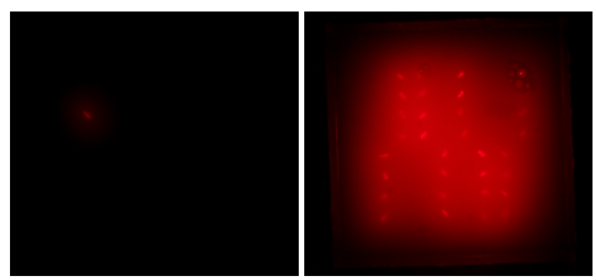
Figure 1: Multiplexed schematic. An 8×8 multiplexed laser array shines a pattern S_i onto a medium of thickness d_{med}.

2.1 Capture Setup

A glass container of size $84 \times 84 \times 45$ mm was filled in increments of 30 ml with a milk/water solution at varying ratios of 3.25% homogenized milk to water. Each solution increment yields a slice of the scene in the vertical z direction with 2.6 mm thickness. Each slice has a depth d_{med} (in cm).

Sixty-four laser diodes were fixed in an 8×8 grid for displaying programmable patterns, controlled by a Raspberry Pi 3+ and an 8×8 laser controller. A 3D-printed chassis embeded the diodes. The chassis restricted translation and rotation of the lasers, except rotation about the axis of a laser.

Figure 2: Multiplexed setup. A physical construction of Figure 1, where the medium is a milk/water solution at different volumes. The laser array is in the grey box under the container.



(a) Captured image of single light source

(b) Captured image of multiplexed light source

Figure 3: Raw camera images

To control the lasers, a sequence of Hadamard coding patterns was programmed in Python. Between each pattern, no light is emitted for a second to allow easier separation of different images in the captured video stream from the camera.

Images were captured as a 30 frame-per-second video with an Olympus E-M1 camera. The camera lens had 60 mm focal length, f/2.8 aperture, and the camera used a relatively high 1600 *ISO*, due to the darkness of the captured images. The camera was focussed at the top of the solution's surface.

The high *ISO* generates noisier images, so the comparison between different noise amounts is more pronounced. We assumed that the amount of light arriving at the camera from the medium that has refraction and reflection events with the glass is minimal.

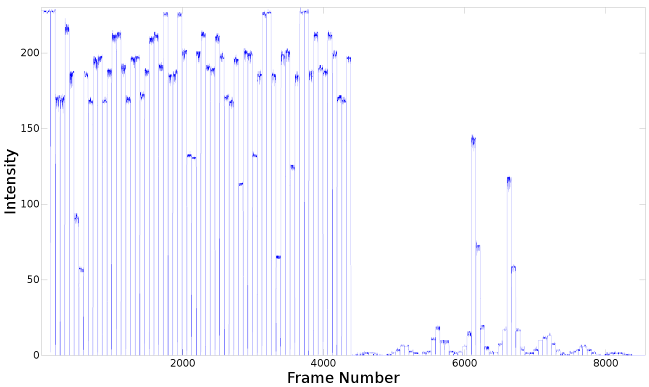


Figure 4: Raw data for one pixel with changing illuminations over time. The left half of the chart with the higher values corresponds to the Hadamard-coded illumination patterns and the right half of the chart corresponds to single sources. The zero values occur at the vertical lines and are easily detected.

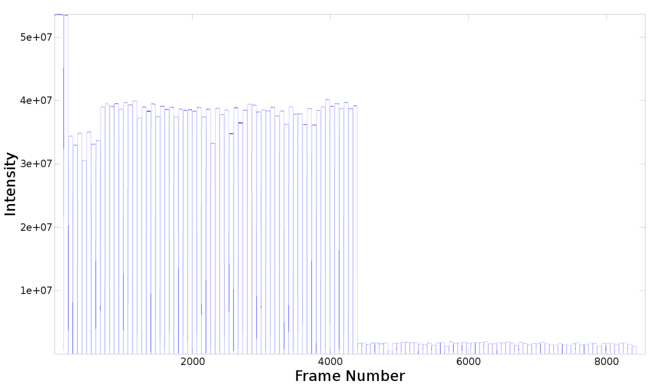


Figure 5: Sums of intensities over all pixels in the video images per frame. The left half of the chart with the higher values corresponds to the Hadamard-coded illumination patterns and the right half of the chart corresponds to single sources.

The program captured raw camera images such as shown in Figure 3. For a single pixel in the camera image, the raw data over a whole video sequence is shown in Figure 4.

The camera recorded a video stream as the different patterns of lasers are illuminated with off frames between each pattern. To extract frames from the video, the video was processed to find positions at which the total image intensity is below some darkness threshold to find the off frames. The time between these zero positions is constant (because the laser controlling program made them constant), so the video frames corresponding to each pattern of lasers could easily be found. To obtain better data for where the sequence begins and ends for each configuration in the video sequence, we considered the sum of intensities over the entire image. This is shown in Figure 5, which in contrast to Figure 4 has easier-to-identify frames in the single source region. These summed intensites were used only to determine the different frames and not calculate the individual light contributions.

In all, 128 laser configurations were tested: 64 for the multiplexed Hadamard codings and 64 for the single-source illuminations. In practice, the duration of each configuration differed by up to a few frames in the video. For the Hadamard configurations, these durations must be equal if we are to solve the linear system for individual light contributions. We thus found the minimum duration, and used raw data of this minimum duration from each configuration. The frames captured over this duration were stored in a constant-size array of n_{numbers} frames for each illumination pattern. From this, a time-varying signal over the minimum duration for each configuration could be obtained for each pixel of the image. The output of this is $64 \times n_{\text{numbers}} \times 2$ video frames grouped by both the Hadamard and single source illumination patterns.

2.2 SNR

For a list of numbers $\boldsymbol{K}$ with length n_{numbers}, we define the SNR as the ratio of the mean to the standard deviation of those values [9],

$$\text{SNR} = \frac{mean(\boldsymbol{K})}{standardDeviation(\boldsymbol{K})} \tag{2}$$

To compute the SNR, the mean and standard deviation of the signal were determined for the (stored) video frames of each configuration. Given a pixel (x, y) that is a distance r_{med} from the centre of the medium, we could obtain the intensities for that pixel over the whole video sequence. For the single source patterns, each group of n_{numbers} frames determined a mean and standard deviation for that illumination pattern at that pixel. This yielded a SNR. All the 64 single-laser signal-to-noise ratios were averaged as well to yield one for the single source illumination patterns $\text{SNR}_{\text{single}}$.

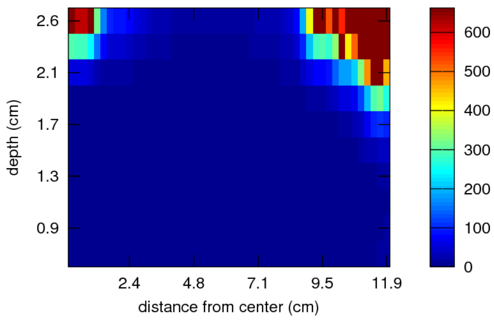
The SNR of the Hadamard encoding, $\text{SNR}_{\text{Hadamard}}$, was calculated similarly, with the exception that each of the n_{numbers} frames was first processed (by solving a linear system) to determine individual laser contributions.

For a given depth of the medium, d_{med}, and radius from the centre of the medium, r_{med}, we obtained a SNR for both the single and Hadamard light sources $\text{SNR}(r_{\text{med}}, d_{\text{med}})$. The radius from the centre was considered an interesting parameter because nothing is mentioned of this in the theoretical analysis.

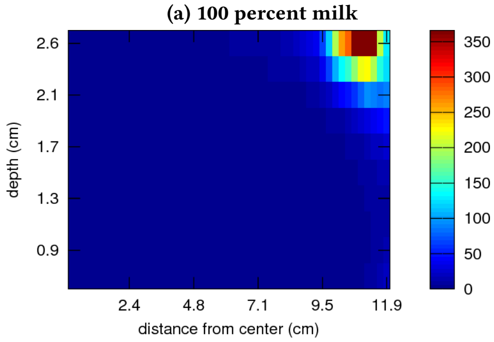
3 RESULTS

Let $\text{SNR}_{\text{R}} = \text{SNR}_{\text{Hadamard}}/\text{SNR}_{\text{single}}$. In Figure 6, the SNR is shown as a function of both distance r_{med} from the centre of the array and depth d_{med} of the milk/water solution. Based on the theoretical equation described by Schechner *et al.* [5], using 64 lasers instead of one, the ratio described in Equation 1 should yield at least a four-fold improvement. However, the experimental results show that this is not always the case.

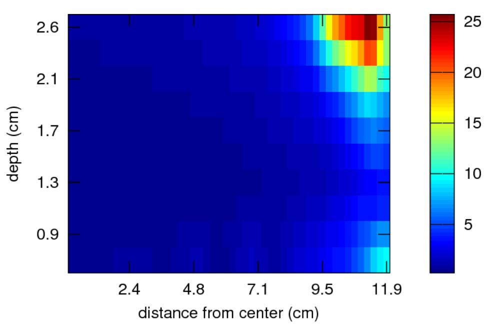
There is an improvement from using multiplexed illumination ($\text{SNR}_{\text{R}} > 1.0$) in most regions as illustrated in Figure 7. The exception occurs with shallower depths and smaller distance from the centre of the medium. There are not many improvements with increasingly transmissive media, as expected. The regions with the most improvement also correspond to the darkest regions of the image.



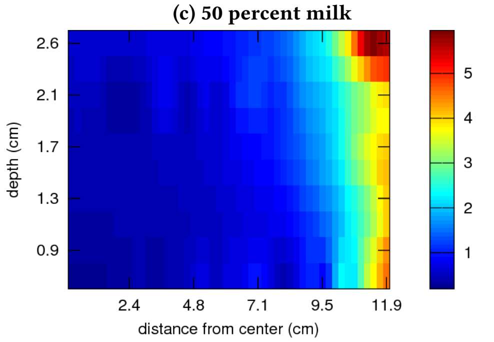
(a) 100 percent milk



(b) 75 percent milk

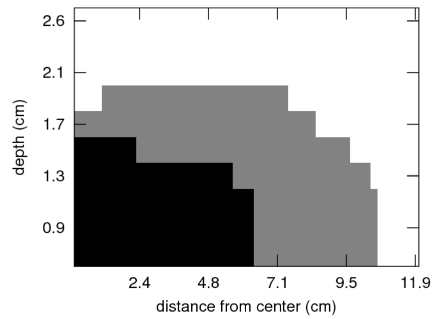


(c) 50 percent milk

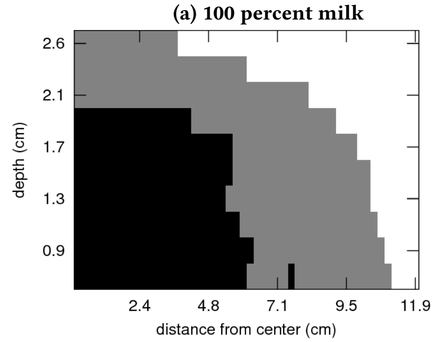


(d) 25 percent milk

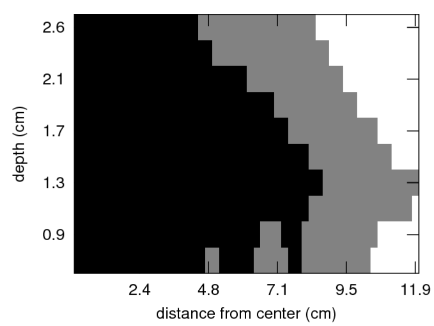
Figure 6: Note the different colour scales on the four images. $SNR_{Hadamard}/SNR_{single}$ for different ratios of milk/water solutions, as a function of vertical slice depth for the milk volume as well as sampled points from the centre of the medium towards the outside. The darkest red colour in the images represents infinity, where $SNR_{single} = 0$.



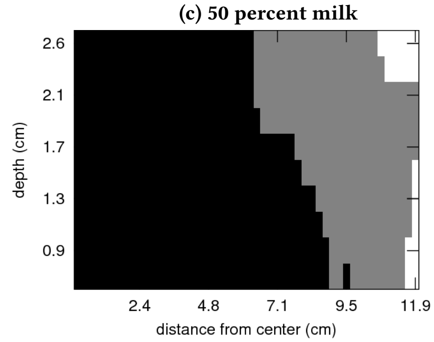
(a) 100 percent milk



(b) 75 percent milk



(c) 50 percent milk



(d) 25 percent milk

Figure 7: Improvements of SNR_R for different ratios of milk/water solutions, as a function of vertical slice depth for the milk volume as well as sampled points from the centre of the medium towards the outside. The black regions have no improvement using multiplexed illumination. the gray regions have an improvement but not as predicted by previous work ($1 < SNR_R < 4$) and the white regions have a better improvement than predicted ($SNR_R > 4$).

The four-fold improvement predicted by previous work does not always appear, depending on the region. The range of improvements depends on the milk/water ratio in the solution. For pure milk it ranges from 0 to 600, whereas for milk diluted down to 25% it ranges from 0 to 6. The more transmissive the medium, the fewer improvements this methodology will yield, as expected. It is interesting to note that the more transmissive the medium, the more the depth becomes irrelevant but the distance from the centre is still important. Also, the improvement ratio $\mathrm{SNR_R}$ approaches infinity in some circumstances because the intensity for the single source image approaches zero, so its signal-to-noise approaches zero as well. This is because the intensity goes below the noise floor of the sensor (i.e. the minimum threshold for capturing photons for this given exposure).

It is also interesting to note that there is a decrease in improvement at the right sides of Figures 6c and 6d. There may be a minimum improvement in terms of depth, where the single source image starts to lose intensity but photons from nearby lasers have not scattered enough to reach that pixel in that given amount of depth. This may be a similar case for the top row in Figure 6a, where there are more scattering photons exiting the middle of the medium from multiple sources than the further outward the pixel is. Finally near the edge, the pixel has almost no light coming from a single source so the multiplexed SNR performs better.

4 CONCLUSION

We have presented an experiment to capture the SNR in scattering media illuminated with single and multiplexed illumination. The SNR_R improves with distance from the centre of the multiplexed laser array and with medium depth, since the average laser distance from the corners is larger than the average laser distance from the centre. This experiment used a liquid medium; however, it could also have used a solid medium if care were taken to slice the medium in a perfectly planar fashion.

This work demonstrated an analysis of a multiplexed lighting setup for variable-depth scattering media. Our analysis shows the improvement of such a lighting setup over a single-light setup, even when the single light is limited by the noise floor of the camera. Without multiplexing, adding more light to a single point would damage the material in question to yield similar SNRs. Future work could derive a physical model based on depth, distance from the centre, number of lights, and distance between lights.

Future experiments could examine how the *SNR* behaves in heterogeneous scattering media, where the noise could be modeled as a function of different material geometries. It would be especially useful to measure the improvements through biological media, although this may be extremely difficult to reconstruct in practice.

A major limitation of our experiment was the lack of dynamic range on the camera. This limitation could be mitigated by using more expensive hardware or multiple, separate exposures.

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