Underwater Rendering with Realistic Water Properties

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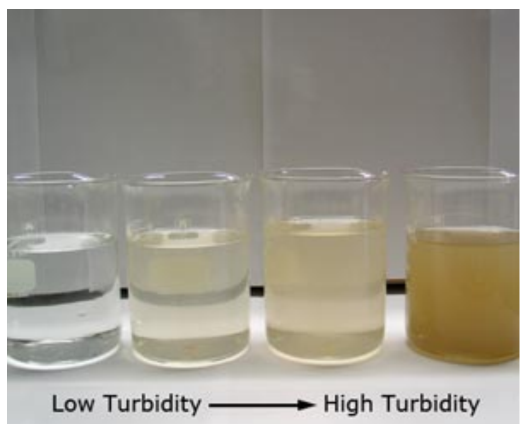
Goal and Motivation

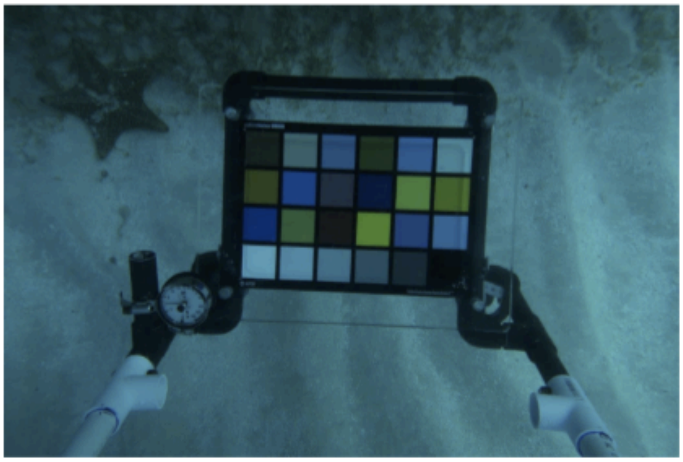
For our project, we implemented a method to simulate light traveling through water with certain properties. These properties include **chlorophyll concentration**, the amount of **dissolved organic matter**, and the **concentration of large and small particles**. With our implementation, a user can easily simulate an underwater photograph taken in a certain type of water, at a certain depth, and with a specific type of lighting.

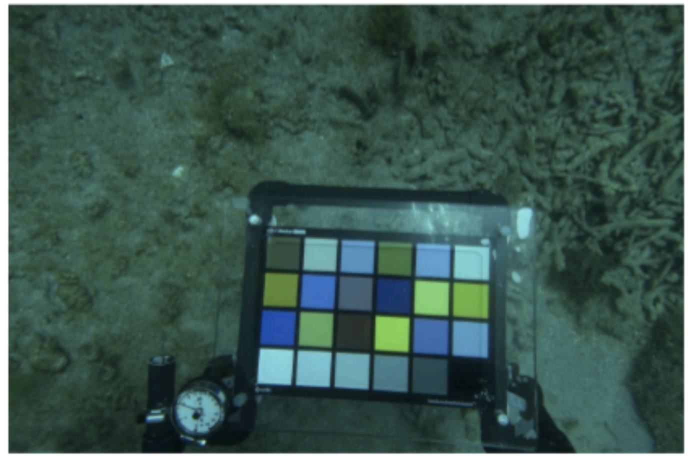
Below, we show example of water with different concentrations of organic matter (left) and turbidity (right).



Many computer vision and image processing researchers are interested in training algorithms specifically for underwater photography. For example, researchers are working on training an algorithm that can classify coral species and evaluate their health based on amateur underwater photographs [1]. Similarly, many people are interested in training image processing pipelines that can reduce color loss or blur seen in underwater images [2]. However, in order to produce reasonable results, these methods typically require very large set of training images. Capturing a large set of underwater images with varying depths and water metrics while having access to the ground truth data for each image is very difficult and costly. In this way, simulating and rendering underwater images with ground truth data (e.g. depth, original color) could be very beneficial for these machine learning applications. The purpose of this project is to create a basic simulator that can capture the effect of underwater photography in different types of water and at different depths.

Because we hope to be able to simulate training data, we were motivated by real training images taken for the purposes described above. For example, the following images of a Macbeth color chart were taken at various locations in the Bahamas at a shallow depth, for the purpose of training machine learning algorithms for underwater imagery.





For our final image, we opted for a more artistic approach that could show off our simulation. We found several images of the Cancun underwater museum, which features a variety of submerged sculptures. We decided to render a final image with an atmosphere and look that was similar to these underwater sculptures.

In this project, Trisha worked primarily on the implementing the new water volume region. Sarah worked primarily on modeling the fish, the scene, and creating the realistic rendering of the scales and fish skin. Both members worked on putting the final scene together.

Implementation

The three main effects water has on light are absorption, scattering, and transmission. This can be written mathematically as $\Phi_i(\lambda) = \Phi_a(\lambda) + \Phi_s(\lambda) + \Phi_t(\lambda)$, which says that the incident radiant power is either absorbed, scattered, or transmitted by a volume of water. These three effects can change drastically depending on specific water properties. At the beginning of this project, we spent time researching the optical properties of water, and found several mathematical models. Once we located and combined the models we wanted to implement, we created a new *VolumeRegion* class called *water*. This class implements the various scattering and attenuation models we found in the literature, which are described in the next two subsections. The user can specify, in a PBRT file, a homogenous water region with specific water properties as shown below:

```
Volume "water"
  "spectrum pureWaterSpectrum" "pureWaterAbsorption.spd"
  "float chlorophyllConc" 2
  "float domConc" 0.05
  "float smallPartConc" 0.01
  "float largePartConc" 0.02
  "point p0" [0.439 0.944 20] "point p1" [-0.649 -0.632 0]
```

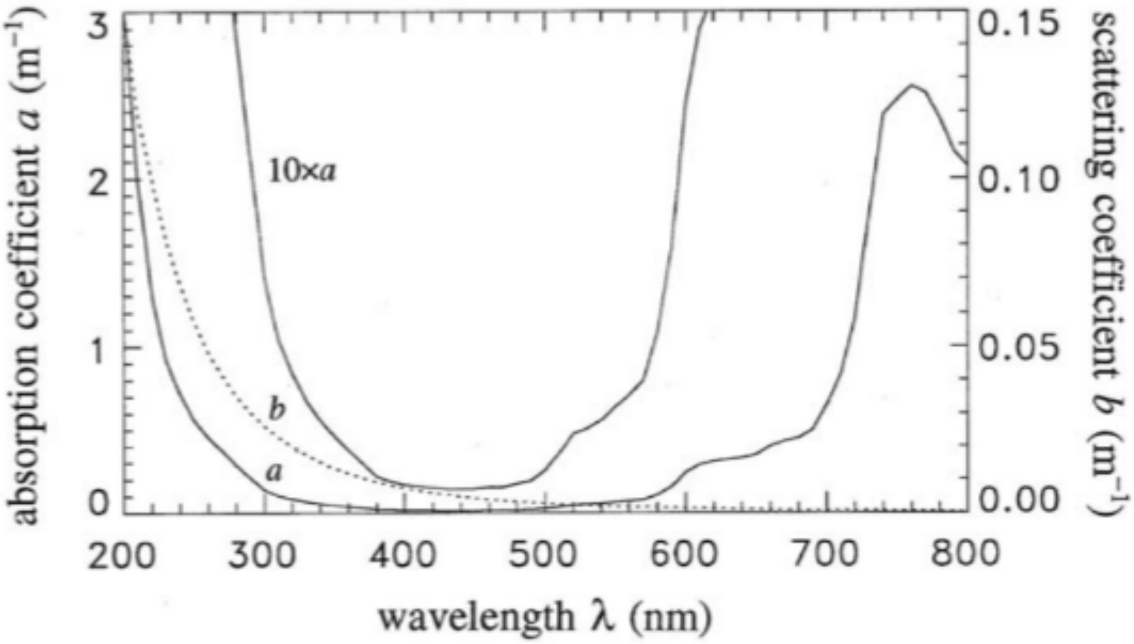
Because most of the models we implemented were wavelength-dependent, we also modified PBRT to use wavelength-dependent phase functions and changed the default *Spectrum* type from *RGBSpectrum* to *SampledSpectrum* (see p.263 in the PBRT book).

Absorption

The three factors we modeled for absorption are:

1. Absorption by pure sea water.
2. Absorption by organic detritus (chlorophyll concentration dependent).
3. Absorption by dissolved organic matter, or yellow matter.

Absorption by sea water is defined from physically measured attenuation values in very clear waters (e.g. Crater Lake, Oregon) made by Smith and Baker (1981) [3]. These measured values are loaded into PBRT and are used to define the first absorption component, $a_{pw}(\lambda)$.



To determine the contribution of organic detrius (debris and waste), we use a combination of a model by Roesler (1989)[4] and a model by Bricaud et al. (1998)[5]. Roesler's model is used to determine the shape of the detrial absorption curve and Bricaud's model is used to link the scale of the curve with the chlorophyll concentration in the water. In the end, we get a model as follows:

$$a_{det}(\lambda) = 0.0124\langle chl\rangle^{0.702} \exp[-0.011(\lambda - 440)]$$

Lastly, the model used to incorporate dissolved organic matter can be found in Bricaud et al. 1981 [6]. Measured values of of $a_y(440)$ at different bodies of water can be found in Light and Water [7], p.92.

$$a_y(\lambda) = a_y(440) \exp[-0.014(\lambda - 440)]$$

Each of these effects results in an wavelength-dependent absorption coefficient. The sum of all absorption contributions result in a final absorption coefficient, which defines which parts of the spectrum is absorbed per unit distance (m^-1) as the ray travels through the volume. We can write this mathematically as $a(\lambda) = a_{pw}(\lambda) + a_{det}(\lambda) + a_y(\lambda)$.

In additon to absorption, the total spectral beam attenuation coefficient also includes the light that is scattered out of the beam. We describe this effect with a scattering coefficient $b(\lambda)$, which we define in the next section. The final attentuation coefficient is then $c(\lambda) = a(\lambda) + b(\lambda)$. Because our water volume is homogenous, the light is attenuated according to Beer's Law:

$$E(z, \lambda) = E(0, \lambda) \exp^{-zc(\lambda)}$$

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Scattering

For scattering, we decided to use a model described by Kopelevich (1983)[8]. This model defines a spectral volume scattering function (VSF) that separates the contribution of "small" and "large" particles. Small particles are those less than 1 um in size, while large particles are greater than 1 um. A body of water may contain certain concentrations of particles described above such as yellow matter or organic detritus, but within those set of particles some may be considered "large" and others may be considered "small." The model is defined as follows:

$$\beta(\psi;\lambda) = \beta_w(\psi;\lambda) + \nu_s \beta_s(\psi)\Big(\frac{550}{\lambda}\Big)^{1.7} + \nu_l \beta_l(\psi)\Big(\frac{550}{\lambda}\Big)^{0.3}$$

$\beta(\psi;\lambda)$ is the VSF of pure sea water. ν_s and ν_l are the concentrations in (ppm) of small and large particles, respectively. β_s and β_l are the VSF of small and large particles, which are described in the paper. ψ is the angle between the incident ray and the outgoing ray.

To get the phase function from the VSF, we divide by the scattering coefficient as follows:

$$\widetilde{\beta}(\psi;\lambda) = \frac{\beta(\psi;\lambda)}{b(\lambda)}$$

The scattering coefficient $b(\lambda)$ is the integral of the VSF over the entire sphere, and therefore describes the total amount of light that is scattered outward. To calculate it we integrate over the Kopelevich model:

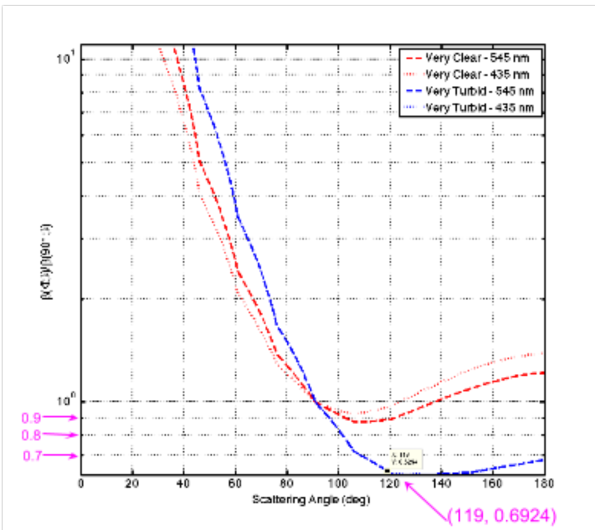
$$b(\lambda) = 2\pi \int_0^{\pi} \beta(\psi,\lambda)\, sin\psi \, d\psi$$

In the *Water* class, the VSF is constructed according to the user's input of small and large particles. Next the scattering function and phase function are calculated. When the volume integrator asks for the phase function between an incoming and outgoing ray direction, we return the result of the Kopelevich model.

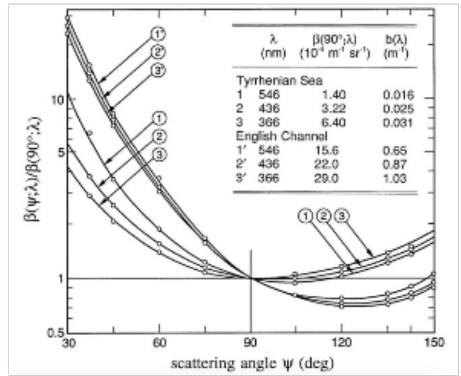
Verification

To verify our model, we compared the output of the ray tracer with plots generated with physical data, measured from real lakes and oceans. These plots were referenced from *Light and Water*. We compared our output for both attenutation and scattering and found that PBRT produced attentuation values and scattering functions that were comparable to the ground truth. For example, we compared the VSF we calculated in the ray tracer with plots from the textbook.

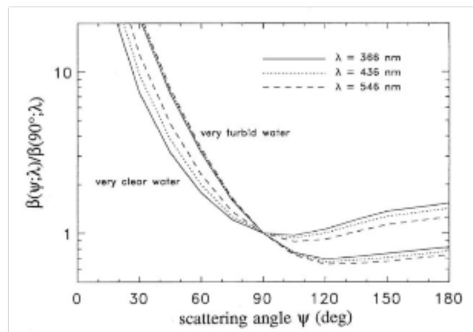
As we would expect, our scattering function matches the Kopelevich scattering function shown in *Light and Water*. This verifies our implementation of the model in PBRT. We can compare these graphs with physically measured values from two types of waters: the Tyrrhenian Sea (very clear) and the English Channel (very turbid.) We can see that the curves of the Kopevelich model follows closely with real world values. *(Note that the slight difference in y-axis between these plots results in a slightly different appearance between the curves.)*



Our scattering output



Measured output ("ground truth")

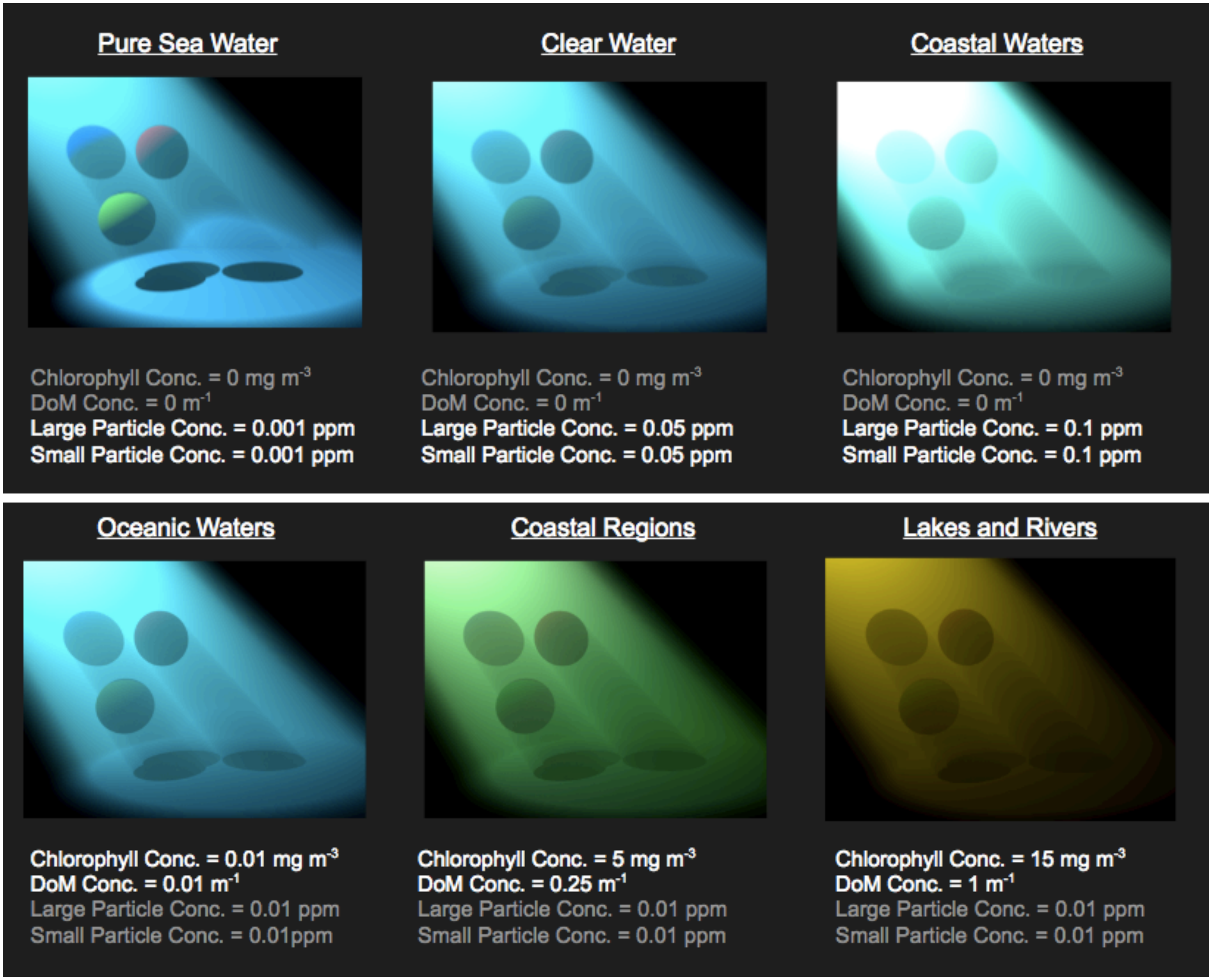


Kopelevich model output

From these results, we can say with some confidence that our simulation of attentuation and scattering is realistic and accurate to a certain degree.

Example Images

To demonstrate the flexibility of our underwater simulation, we rendered a test scene in different types of water. All parameter values are based off of real physical, measured values found in *Light and Water.*

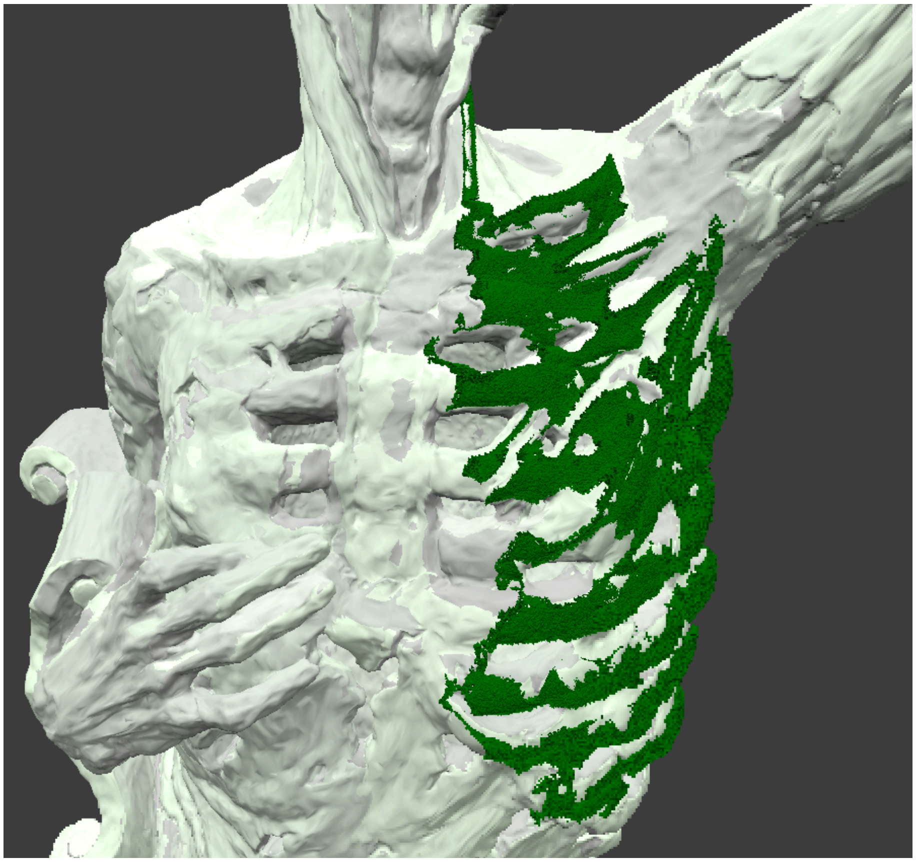


Modeling Final Image

For our final image, we wanted to use these effects to model an environment that was both artistic and realistic. Our inspiration for this scene was an underwater art museum with sculptures designed by Jason Taylor. Here is an example of his work:

The placement of art in an environment where visibility is impaired was fascinating to us, and we wanted to explore how we could accurately capture this art form and how we could integrate nature into the scene.

We began with a 3D model of a statue. To create moss on the structure, we duplicated and deformed the skeleton to get an entity that correctly formed to the original statue. Additionally, we deformed the surface of both the moss and statue to be more noisy and flawed- thus becoming more realistic.



The fish was difficult to model because we wanted it to internally scatter light in a realistic way. Because of this, we created the fish in 3 parts. The body of the fish modeled the soft body tissue. This acted as a primary covering, because in a real fish there is still a soft body under the scales. The fins and tails are also made up of this soft, thin tissue. Over that, we set a layer of scales. This layer included a bump map that could reflect light properly, and covered the main body portion of the fish. We spent time observing goldfish in a tank nearby to get these scales right. The head of the fish is also a different material. It is not scaly but also not as translucent as the rest of the fish. Finally, we modeled a simple skeleton that would show through when light bounced within the fish. These parts in conjunction are seen here (although the head is not finished):

Final Image

Putting these models in the environment proved challenging. At first, we had almost no visibility

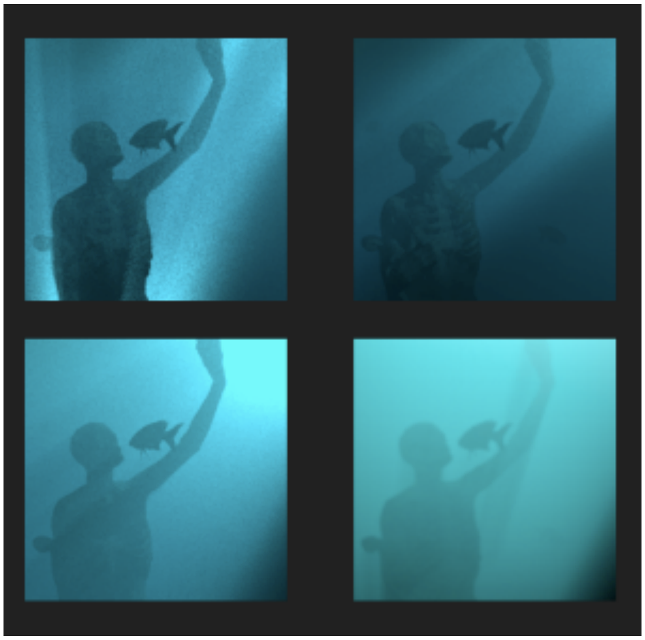
As you can see in this image, all objects are black and silhouetted. We discovered later that the problem was that the scale was too large. Each unit in pbrt represented a meter. Since our model for water was physically accurate, this meant that there were around 15 meters of water (and therefore light attenuation) between our camera and the model. Scaling the scene down allowed us to see color and detail. The fact that this worked, helped prove to ourselves that our light model was realistic.

Another issue we had was placing a *kdsubsurface* material within the water. Using the subsurface material rendered the fish distinctly darker than its matte counterparts.We hypothesized that this was because the light, while bouncing around in the fish, was also attenuating within the water material. We attempted to create a bounding box around the fish that had no attenuation, but the lighting of the scene made this impossible. In the end, we decided to hack the scene and put a small point light in the fish. This addition of light compensates for the light that is lost due to the bouncing.

Finally, to light the scene, we projected a caustics texture (as recorded from the shallow ocean floor) through 22 meters of water. This allowed the light to attenuate in a realistic way, and create accurate beams of light running through the water.

To decide how to light the water, we read a lot of articles about underwater lighting. Because this is a challenge in real life, there is a lot of information about how scuba diver photographers capture underwater scenes. Applying these findings to our image, we found that the same techniques work. This, again, shows that our water simulation is behaving realistically, and helped guide us to lighting the scene. This also highlights another use of our simulation; one can potentially design an underwater lighting rig in our simulation to help guide the construction of a real rig.

Below are some example of different lighting setups that we tried.



Here is our final image.

References

[1] Blasinski, Henryk, and Joyce E. Farrell. "Simulation of Underwater Imaging Systems." Imaging Systems and Applications. Optical Society of America, 2015.

[2] Yamashita, Atsushi, Megumi Fujii, and Toru Kaneko. "Color registration of underwater images for

underwater sensing with consideration of light attenuation." Robotics and automation, 2007 IEEE international conference on. IEEE, 2007.

[3] Smith, Raymond C., and Karen S. Baker. "Optical properties of the clearest natural waters (200?800 nm)." Applied optics 20.2 (1981): 177-184.

[4] Roesler, Collin S., Mary Jane Perry, and Kendall L. Carder. "Modeling in situ phytoplankton absorption from total absorption spectra in productive inland marine waters." Limnol. Oceanogr 34.8 (1989): 1510-1523.

[5] Bricaud, Annick, et al. "Variations of light absorption by suspended particles with chlorophyll a concentration in oceanic (case 1) waters: Analysis and implications for bio?optical models." Journal of Geophysical Research: Oceans 103.C13 (1998): 31033-31044.

[6] Bricaud, Annick, Andre Morel, and Louis Prieur. "Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domains." Limnology and oceanography 26.1 (1981): 43-53.

[7] Mobley, Curtis D. Light and water: radiative transfer in natural waters. Academic press, 1994.

[8] Kopelevich, O. V. "Small-parameter model of optical properties of sea water."Ocean Optics 1 (1983): 208-234.