Underwater Color Correction

Thor Olson; Electronics for Imaging; Minneapolis, MN

Abstract

An introduction to light in an absorbing, scattering medium is offered, with application to correcting the colors in underwater photographs. The "waterlight" model is presented which quantifies the amount of light scattered in the direction of the camera from the medium itself. A spectral model for ocean water is described along with a method to represent it in three bands (e.g. RGB). Given these models, the radiance of a diffuse reflector at known depth and distance can be computed. At infinite distance, this becomes the "abyss color", a new and useful concept with which to estimate camera response, and the water parameters. The color correction procedure for a given depth and distance is outlined and illustrated. Unknown causes of color shifts from camera or water are addressed via a "blue balance" transform, which maps the recorded abyss color to the modeled abyss color. A compact vector expression for the correction is presented and examples where it is applied to underwater scenes are provided.

Keywords*: Underwater photography, color correction, whitepoint adaptation, absorbing medium, scattering medium, abyss color, waterlight, blue balance.*

Introduction

Over the last few decades there has been a growing collection of research into the topic of underwater imaging as ever more capable underwater probes have been developed. This paper has a more modest goal than the cutting edge research listed in the (2017) survey by Hu, et. al. [6], but fits within its "software-based, physical model" category, and is a response to the improvements (and waterproofing) of consumer cameras and the increasing popularity of taking pictures underwater.

Digital cameras have evolved sophisticated systems to convert raw sensor data into pleasing photographs. The main operation is to transform the sensor values into a standardized color representation, compensating for the illumination in a scene to which a viewer has adapted, but the sensor of course, has not.

Most photographs are made on land, with the camera immersed in a highly transparent medium, air. When it is taken underwater, the medium becomes only somewhat transparent; it has properties that absorb and scatter light at even small distances, and it does so in a wavelength-dependent manner. In such an environment, the automated response of the camera is fooled, and even manual settings are unable to remove the effects of the colored medium. The result is an image that is rarely satisfying without subsequent image adjustments.

Even the powerful tools of modern digital photography, if unguided, will not easily yield a color-correct rendition of an underwater scene. It is the purpose of this paper to provide simplified guidance for correcting colors in underwater photographs. This guidance relies on an optical model of the water, and a newly introduced construct: the "abyss color", the color of the deep view, which can be used to augment the model of water characteristics that the camera is submerged within, and of the camera response itself.

The Nature of Light

In our situation of taking pictures underwater, photons are created by radiation from the sun or emissions by atoms in a flash tube or LED. They can end in only one way, by absorption in the water, or by the materials in the water. Everything in between these events is a redirection of their travel plans [5].

Once in transit, a photon will travel until it encounters the atoms or molecules of some material. If the photon is not absorbed, it will be redirected, scattered. The macroscopic behavior of absorption and scattering are represented by simple exponential attenuation equations:

$$L_{ab}(x) = L(0)e^{-\beta_{ab}\,x} \tag{1}$$

$$L_{sc}(x) = L(0)e^{-\beta_{sc}\,x} \tag{2}$$

where $L_{ab}(x)$ and $L_{sc}(x)$ are the radiances due to absorption and scattering at position x, β_{ab} is the absorption coefficient, β_{sc} the scattering coefficient. These are sometimes summed to an equivalent "extinction" coefficient, $\beta_{ex} = \beta_{sc} + \beta_{ab}$.

When we need to know where the out-scattered energy goes, we use its angular probability density function Φ(θ), sometimes (confusingly) called the phase function. Φ(θ)dω is the probability that a photon will be scattered into the small solid angle dω in direction θ (the deviation from original direction). It is a probability density, so its units are sr^{-1} and its integral over all directions yields one [1]:

$$\int_{\Omega} \Phi(\theta)d\omega = 1 \tag{3}$$

These three values, β_{ab}, β_{sc}, and Φ(θ) will be used to characterize our absorbing, scattering medium (water). They are functions of wavelength, though in this paper the types of scattering considered (small particles, spherical particles), will be limited to where the scattering probability density Φ is independent of wavelength.

The Nature of Water

There are additional constituents to ocean water than just its H2O, which makes a single representation for it not possible. Different concentrations of salinity, dissolved organic matter, phytoplankton, and suspended debris all contribute to the wide range of water color and clarity found in the world. This is one reason that model-based underwater color correction is difficult.

Bio-optical models have been developed that parameterize these different components [4]. The spectral contributions to absorption and scattering for specific amounts and concentrations are shown in figures 1 and 2. Although the bio-optical model can represent any number of contributing elements, we still end up with a single net value for the absorption coefficient (at each wavelength), a single net value for scattering coefficient (at each wavelength), and a scattering distribution function (independent of wavelength).

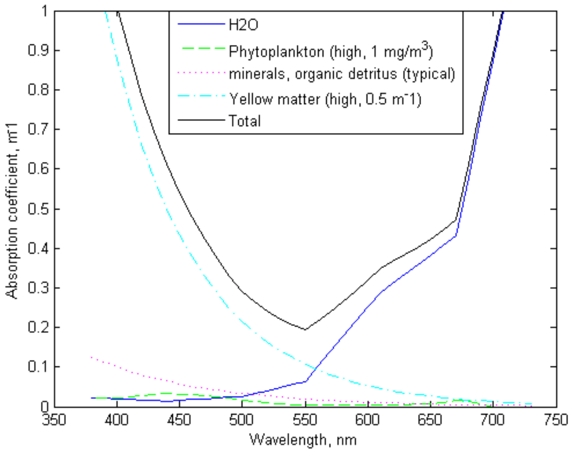

Figure 1. Absorption coefficients as a function of wavelength for various constituents of ocean wate

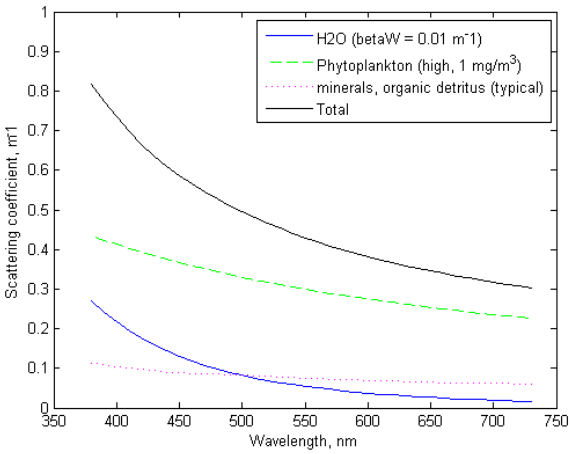

Figure 2. Scattering coefficients as a function of wavelength for various constituents of ocean water.

The Waterlight Model

Inspired by and following the "airlight model" described in [2], we rename it for our underwater application. We initially consider the simplest of geometries, figure 3. The light source we use is the sun, subtending 0.5 degrees.

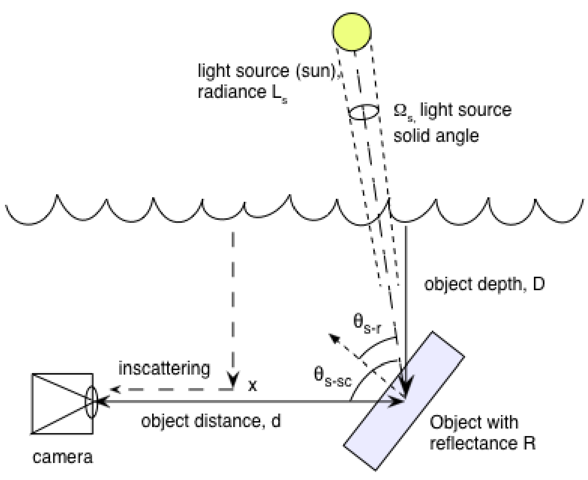

Figure 3. Our underwater geometry.

We will consider two components of light along any given ray from the observer or camera to a reflecting object. One is the direct light from the source, attenuated along the path reaching the object at depth D, reflecting off it in the direction of our camera. The reflected light is further attenuated over the distance to the camera, d.

The other light component that enters the camera along a specific ray includes any additional light that scatters into the ray's direction. Because water is a scattering medium, there will be small amounts of light coming from the overhead source, that will be scattered into the direction of our camera. Contributions will come from points all along the path from the camera to the object's surface, or to infinity if the object does not intercept the ray. This will be called the "inscattered" component, or “waterlight”.

There are additional components that enter the camera along a given ray that involve multiple reflection and scattering events. This paper does not address that additional complexity, but treatments of them are found in some of the methods included in surveys [3] and [6].

We can obtain expressions for the radiance seen by the camera for the two components. In the absence of any influence by the medium, the direct (reflected) radiance L_r in the direction of the camera due to an idealized reflecting surface can be described:

$$L_r = \frac{R\cos(\theta_{s-r})}{\pi} L_s \Omega_s \tag{4}$$

where θ_{s-r} is the angle between the sun and the reflecting surface normal, $L_s\Omega_s$ is the irradiance from the sun (solar radiance L_s times its solid angle).

But the medium is water, not vacuum, and the light from the source is attenuated by two mechanisms, absorption, and outscattering (scattering away from the ray). What remains reflects off of the object, and this reflected light is also attenuated by absorption and outscattering before being detected at the camera. The attenuation of the radiance is modeled by an exponential "extinction" coefficient:

$$L_r = e^{-\beta_{sc} d} \frac{R\cos(\theta_{s-r})}{\pi} e^{-\beta_{ab} D} L_s \Omega_s \tag{5}$$

In our simple geometry the light is directly overhead so the incident light depends only on depth D. We also consider a purely horizontal view from the camera, so the captured radiance depends on distance d. Depth D and distance d are simplifications of the actual distances involved when it is not noon, or we are not looking straight out. They may be generalized to geometries other than pure vertical and horizontal.

In addition to the attenuated reflected light, there is also some "contamination" by inscattering. This occurs along the path from the object to the camera, where light incident on the water along the viewing ray is scattered into the direction of the camera. We must integrate the scattering contributions from each scattering element along the path:

$$L_{sc} = \int_0^d \int_\Omega L(\omega) \beta_{sc} \Phi(\omega, \theta_{sc})\, d\omega\, dx \tag{6}$$

This inscattered light, the waterlight, occurs along the entire path from object to camera, but of course it is influenced by absorption and scattering (extinction) just like any other light traveling in this direction. Using our solar illumination, the radiance of the additional light due to inscattering along this path is:

$$L_{sc} = \int_0^d e^{-\beta_{sc}x}\beta_{sc}\Phi(\theta_{s-sc})\, e^{-\beta_{ex}D}L_s\Omega_s$$

$$L_{sc} = \frac{\beta_{sc}}{\beta_{ex}}(1 - e^{-\beta_{ex}d})\Phi(\theta_{s-sc})\, e^{-\beta_{ex}D}L_s\Omega_s \qquad (7)$$

Color Representation and the Abyss Color

With our simple geometry, we can consider what a diffuse white reflecting surface might look like when it is positioned at various depths and distances. The expression for the detected radiance is the sum of our two components (equations 5 and 7):

$$L(d, D) = L_r + L_{sc}$$

$$L(d, D) = \left\{e^{-\beta_{ex}d}\left(\frac{R\cos(\Theta_{s-r})}{\pi} - \frac{\beta_{sc}}{\beta_{ex}}\Phi(\theta_{s-sc})\right) + \frac{\beta_{sc}}{\beta_{ex}}\Phi(\theta_{s-sc})\right\} e^{-\beta_{ex}D}L_s\Omega_s \qquad (8)$$

Some sample reflection spectra from illuminant E, at a various depths and distances are shown in figures 4 and 5.

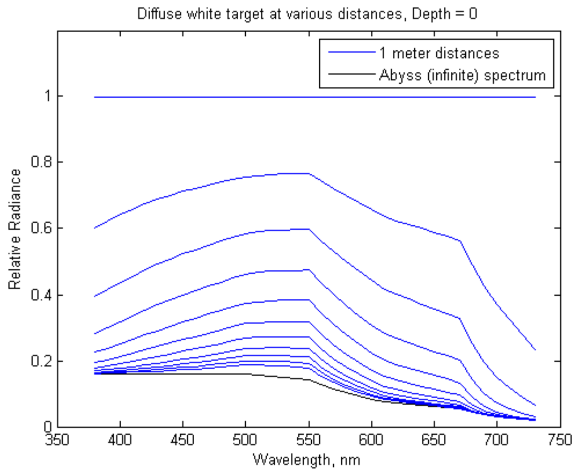

Figure 4. Spectrum of light (from illuminant E) reflected from a white surface just below the ocean surface at increasing distances.

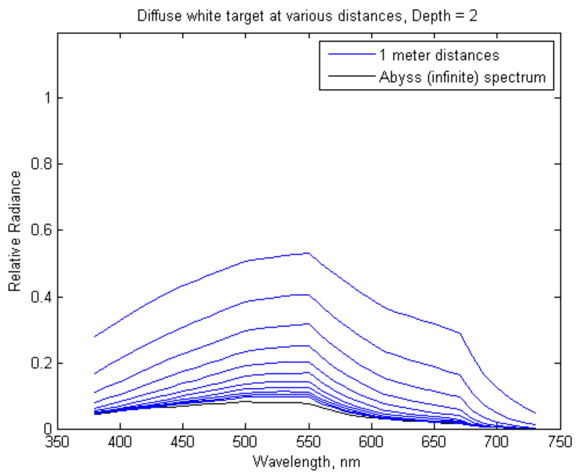

Figure 5. Spectrum of light reflected from a white surface at a depth of 2 meters for increasing distances.

We can see the spectra converging toward a limiting shape as we increase distance. That shape depends on the depth, which shapes the incident spectrum on the object surface and on the water in the line of sight to it. Beyond some distance, the object itself no longer matters, the light is entirely from the inscattering along the line of sight. We call this the "abyss color", as it represents the view into an infinite volume. Technically, this is a "horizontal abyss" where the incident spectrum is constant along the line of sight. The color for a more conventional use of the term abyss, is what results when looking straight down-- the incident spectrum attenuates at each point along the line of sight.

We can weight the spectra by the color matching functions to obtain tristimulus values, and then map them to RGB display values. The conventional integral or summation is performed:

$$X = \pi \frac{\sum L(\lambda_i)\bar{x}(\lambda_i)}{\sum \bar{x}(\lambda_i)} \qquad (9)$$

The tristimulus values for Y and Z are obtained similarly. The factor π converts from a radiance to a diffuse reflectance value. Figure 6 shows representations of the colors seen as a function of depth and distance for a specific model of ocean water.

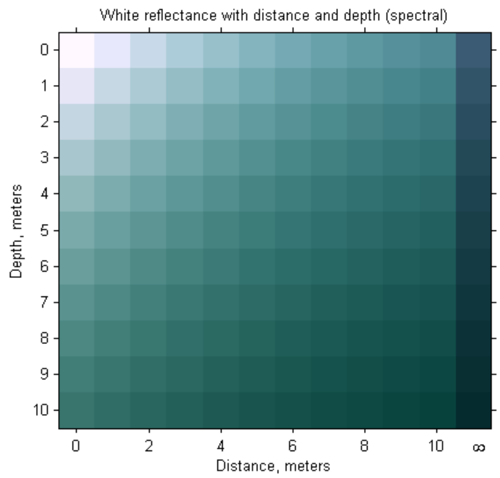

Figure 6. Color patches representing the white reflector at increasing depths and distances for a specific model of seawater. The "abyss color" is shown in the rightmost column.

Although we have full spectral representations for the scattering and absorption coefficients, it will be convenient for the purposes of correcting underwater photographs, to have a version of them that works for a three-band representation of color. We approach this by considering how we would obtain the coefficients for a specific wavelength given samples of a reflecting surface at a given distance, and at infinity, the abyss color. We can use "depth normalized radiances" to remove the common factors of depth-attenuated irradiance. The abyss color, L_∞ and the observed radiance at reference distance d are:

$$L_\infty = \frac{\beta_{sc}}{\beta_{ex}}\Phi(\theta_{s-sc}) \qquad (10)$$

$$L_d = e^{-\beta_{ex}d}\left(\frac{R\cos(\theta_{s-r})}{\pi} - \frac{\beta_{sc}}{\beta_{ex}}\Phi(\theta_{s-sc}) - \frac{\beta_{sc}}{\beta_{ex}}\Phi(\theta_{s-sc})\right) + L_\infty \qquad (11)$$

We solve this for β_{ab} and β_{sc}:

$$\beta_{ex} = \frac{1}{d}\ln\left(\frac{\frac{R\cos(\theta_{s-r})}{\pi} - L_\infty}{L_d - L_\infty}\right) \tag{12}$$

$$\beta_{sc} = \frac{\beta_{ex}}{\Phi(\theta_{s-sc})} L_\infty \tag{13}$$

$$\beta_{ab} = \beta_{ex} - \beta_{sc} \tag{14}$$

This solution works for a specific wavelength, and suggests that we can perform an analogous computation for a weighted combination of wavelengths and obtain an equivalent set of scattering and absorption coefficients. The coefficients for tristimulus channels for example, would weight the spectra of the abyss and reference colors by the color matching functions and perform the calculation in XYZ.

If a camera's spectral sensitivity is known, it can be used as the weighting, and RGB coefficients obtained. Usually that level of camera design detail is not available. In its place we can transform the XYZ coefficients into the RGB color space of the image. This is not the same as a proper RGB spectral weighting, but provides a reasonable estimate for what is already a loss of information when going from a full spectral model to a three band representation.

Color Correction Procedure

The camera sees light from two sources, the (wanted) light reflected off of the object, attenuated by its distance from us, and the (unwanted) light scattering off of the intervening water into our direction (the "waterlight"). To correct this attenuated and contaminated signal, we simply subtract the unwanted in-scattered light, and then amplify what remains back to the level where it was reflected at the object. We will have effectively removed the water and replaced it with vacuum.

Of course there are some complexities. The correction will be only as good as our model for the absorption and scattering of the water. And we must know the distance to the object. But even if we do not know these things exactly, we may find an improvement.

Let's say for the moment that the camera has accurately recorded the scene, and we know our depth D, and the distance d, to the object that we wish to color correct.

The light reflected from the object that finds its way directly to the camera was given by equation 5, the unwanted inscattered waterlight by equation 7. Both are influenced by the spectrum of the source, which attenuates with depth. We drop the solar irradiance term, considering it an overall exposure normalization, leaving the attenuation exponential. Since this is common to both reflected and scattered components, we can apply a correcting scale factor, effectively a "depth adaptation." If our pixel amplitude is represented by p, step 1 of the correction procedure is to apply this gain.

$$p_1 = e^{\beta_{ex} D} p \tag{15}$$

To correct for the unwanted waterlight, we simply compute it for distance d and subtract it. This is a constant over the whole image.

$$p_2 = p_1 - \pi L_{sc}(d) \tag{16}$$

We now determine for the remaining light, its attenuation along the path. We multiply the signal to compensate for it. This recovers the original reflectance of the object:

$$p_3 = e^{\beta_{ex} d} p_2 \tag{17}$$

In principle, we do this correction at every pixel for every wavelength because the scattering and attenuation is wavelength dependent. In practice, we do not have a full spectral image, we have an RGB image, and we must use the equivalent attenuation and extinction coefficients for our three spectral bands.

Figure 7 shows the result of this three step correction. The abyss color and the waterlight color for a depth of 3m and a distances of 2 meters and 6 meters are shown as patches. The first image is the uncorrected original, the second adapts it to the surface, the third subtracts the waterlight, the last multiplies by the reciprocal of the attenuation.

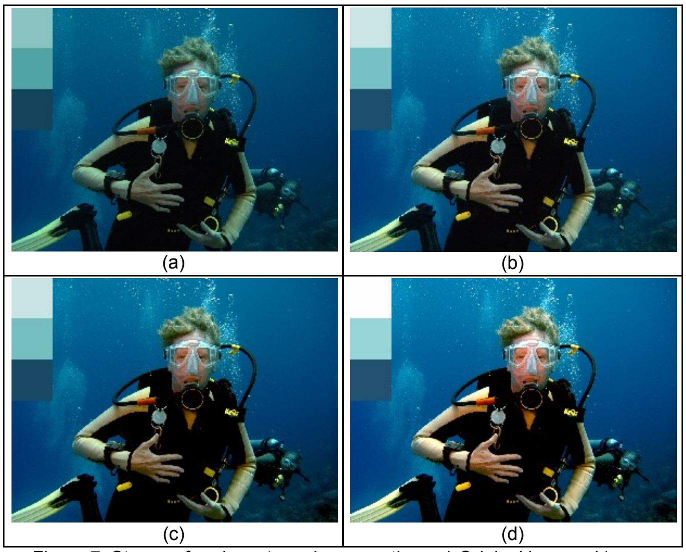

Figure 7. Stages of underwater color correction. a) Original image. b) "Depth adapted" to the surface, D=3m. c) "Waterlight" from distance d=2m to diver removed. d) Gain applied to compensate for the 2 meter extinction distance. The patches are representations of a reflecting white at d=2, d=6, and d=∞.

These are global operations on the image, correcting it for a given depth and a single distance. We can select a different depth, say 4.5m, and a distance of 6 meters, and perform the correction. The result is in figure 8, showing a different part of the image looks better, while the near object is now over corrected.

An obvious extension of this correction procedure is to incorporate a "distance map" and apply the appropriate offsets and gains for each distance. Figure 8 shows an example using a simple distance map painting based on the objects in the photo.

Blue Balance

The method just described assumed that our image accurately captured (within some fixed exposure factor) the underwater scene. Unfortunately, there are many obstacles to that accurate representation. Cameras attempt to help us by applying a white balance transform. This will skew the results of the correction since the recording of neutral will not match our model of it. To address this problem we would like a way to transform our image into the color model we are assuming prior to our correction procedure.

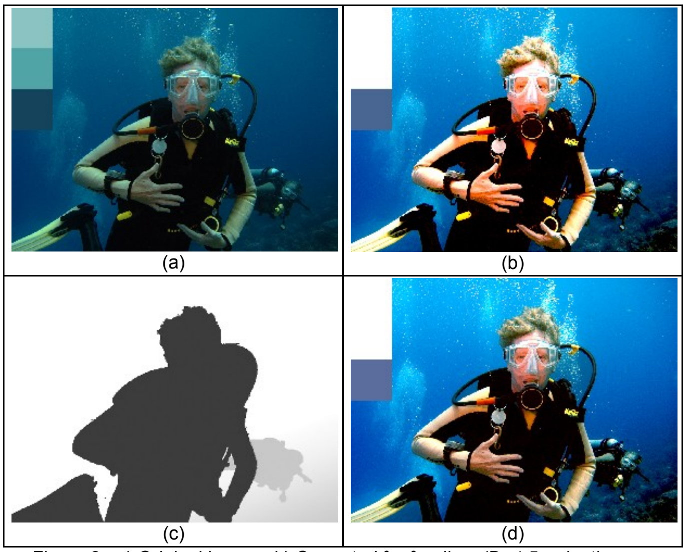

Figure 8. a) Original image. b) Corrected for far diver (D=4.5m depth, d=6m distance). c) Distance map, near diver at d=2m, far diver at 6m. d) Distance map corrected image.

In many underwater photos, the abyss color is recorded as the blue background color in the distance where details and objects can no longer be seen. The actual color recorded will depend on the internal details of the camera sensitivity and the whitepoint balancing algorithms used in rendering the image.

These details are entirely unknown to us, but we can make an effort to supplement them. Just as we use a white adaptation procedure to convert a recording of neutral in a photo to a desired whitepoint, we can perform a similar operation on our recording of the abyss color to map it to our modeled "bluepoint". For obvious reasons, this will be called blue balancing.

The procedure is exactly the same as a whitepoint adaptation, we convert the measured tristimulus representation to a cone space, and then find the cone gains that, when transformed back, yield the desired modeled tristimulus of the abyss color. The procedure uses the modeled abyss color from equation 8 with d=∞, weighted by the color matching equations to obtain an XYZ value, call it $\mathbf{a}_{\infty,\mathrm{model}}$. The measured abyss color, converted to XYZ is $\mathbf{a}_{\infty,\mathrm{meas}}$. There will in general be an exposure scale factor between them, which we would like to exclude, so we estimate it by taking the ratio of their luminance (Y) components

$$k_{exp} = \frac{\mathbf{a}_{\infty,meas,2}}{\mathbf{a}_{\infty,model,2}} \tag{18}$$

We now transform the tristimulus values to cone space using a suitable matrix $\mathrm{M}_{\mathrm{cone}}$, and form the cone weightings:

$$w_i = k_{exp} \frac{\mathbf{M}_{cone}\mathbf{a}_{\infty,model,i}}{\mathbf{M}_{cone}\mathbf{a}_{\infty,meas,i}} \tag{19}$$

The blue balance matrix that transforms measured (photographed) tristimulus values to model tristimulus values is:

$$\mathbf{B}_{XYZ} = \mathbf{M}_{cone}^{-1}\mathbf{W}\mathbf{M}_{cone} \tag{20}$$

where W is the diagonal matrix formed from the cone weights w_i. We can obtain a transform that converts RGB samples by enclosing within color space transforms:

$$\mathbf{B}_{RGB} = \mathbf{M}_{XYZ\to RGB}\mathbf{B}_{XYZ}\mathbf{M}_{RGB\to XYZ} \tag{21}$$

Although a camera does not "adapt" in the same way the human visual system does, it contains the mechanisms to mimic it. In the absence of knowing the exact transform used by the camera, we take advantage of the adaptation procedure to bring the abyss blue in line with our modeled expectation of it.

The blue balance matrix must be applied before the correction procedure outlined above. We can combine it into the depth adaptation step however. The matrix representation for the full correction procedure on pixel p now becomes:

$$\boldsymbol{p}' = \mathbf{N}(\mathbf{D}\mathbf{B}\boldsymbol{p} - \pi\boldsymbol{L}_{sc}(0,d)) \tag{22}$$

where **B** is the blue balance matrix, **D** is a diagonal matrix made of the depth adaptation factors (equation 15), and **N** is a diagonal matrix that normalizes the amplitudes, compensating for distance (equation 17).

Estimating Model Parameters

We previously showed how to obtain the absorption and scattering coefficients given the abyss color spectrum and the spectrum of a reference white card at a given distance (eq 12-14). We did this to obtain equivalent three-band coefficients by weighting the spectra and performing the calculation. In this case, the colors we started with were spectrally modeled.

If we have actual measurements of the abyss and reference distance colors, we can make the same calculation and obtain estimates for the actual coefficients for the water we in. Care must be taken however for several hazards.

An adequately large, but not too large, reference distance is required in order to obtain reliable estimates. The estimate is highly sensitive when the reference is too close to white (near distances), or becomes too close to the abyss color. Reference distances that are approximately equal to the (reciprocal) extinction coefficient seem to work well for this purpose.

Further, we are assuming that the camera has accurately captured those colors. If there is error, we will be unable to distinguish the color shifts intrinsic to the water from the color shifts the camera introduced. When this is the case, an iterative procedure is sometimes successful at converging on a set of coefficients that are compatible with the blue balance matrix that results. Each iteration generates a new set of coefficients, which yields a newly modeled abyss color, which is then used to update the blue balance matrix.

Summary

We have described an approach to correcting underwater photographs that is based on the absorption and scattering characteristics of water. A model for describing the water included spectral characteristics of multiple components that can be found in ocean water.

A simplified lighting geometry was used to illustrate the model, with the sun at zenith, and the camera looking directly horizontal. The concept of waterlight was introduced, the redirected light scattered from the volume of water between the camera and the object. By evaluating the attenuation and including the waterlight, we can model the radiance of a diffuse reflector placed at a given depth and distance.

To correct a photograph we perform a virtual transport to the surface by a depth adaptation, subtract the waterlight, and then undo the effects of attenuation with distance.

When the camera characteristics are unknown, we can perform a "blue balance" that transforms the recorded infinite abyss color to match the color of our water model. When the water model parameters are unknown, we can make estimates of them based on the recorded abyss color, and that of a neutral reflector at a reference distance. When both water and camera characteristics are uncertain, an iterative technique can provide estimates.

Even with only approximate values for the water model and the camera, it is possible to gain significant improvements in contrast and color by applying this underwater color correction technique.

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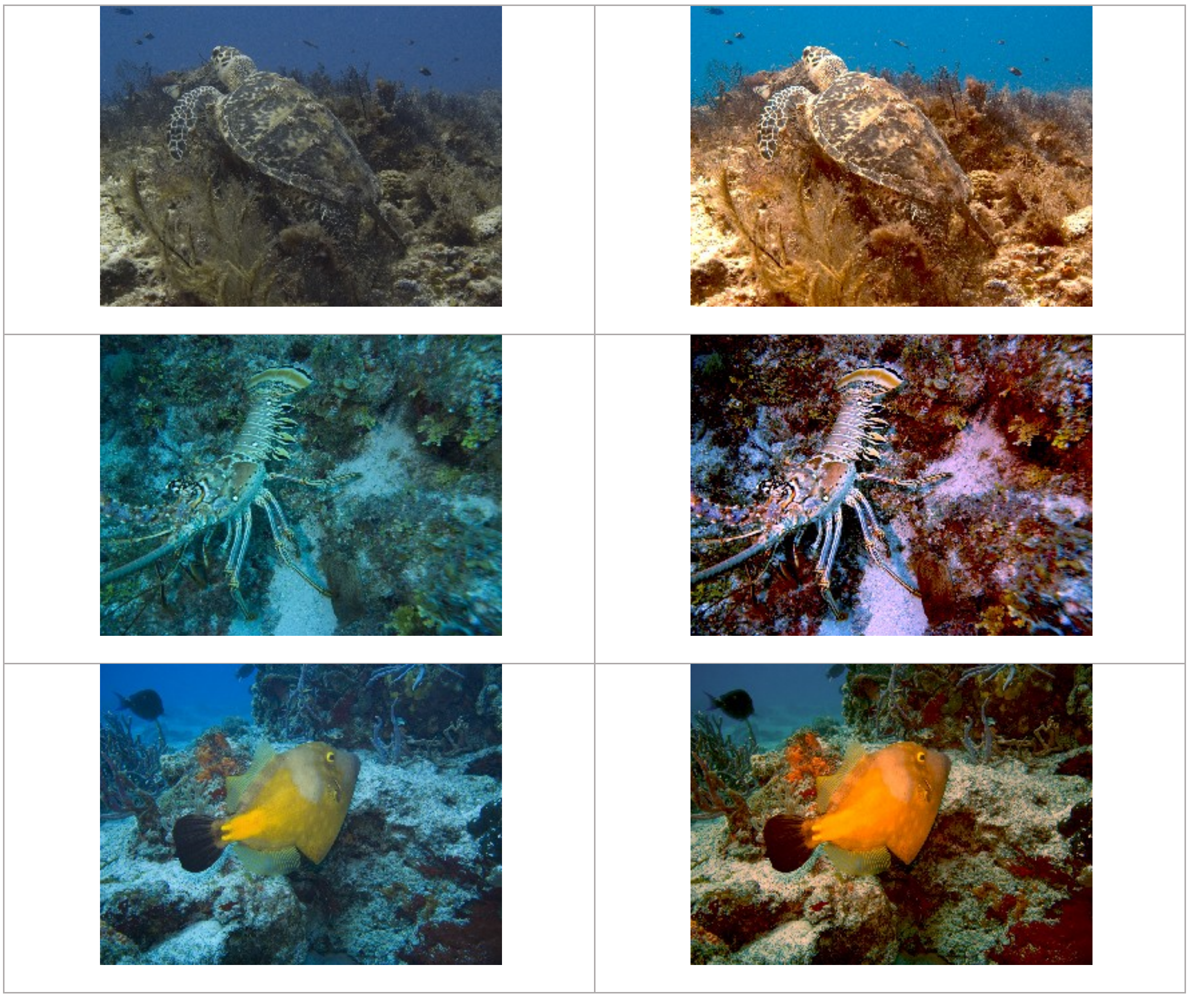

Figure 9. Examples of underwater color correction using the methods described in this paper. Photos courtesy Dave Larsen, University of Florida, Jacksonville.