A Link Budget Approach to Specifying Lights and Cameras for Underwater Applications

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***Abstract*— Specifying lighting and cameras can be a complex and challenging task for any photographer or videographer. When dealing with the underwater environment the challenges grow exponentially. Anyone who has worked around, on, or under the ocean is well aware that conditions can quickly change dramatically. Visibility, ambient light conditions, and even the power to the equipment in use, can have a significant impact on the quality of underwater images. Acknowledging this variability, however, does not relieve us of the need to specify cameras and lighting systems capable of operating in extreme environments. In this paper we will look at some of the technical aspects of specifying lights and cameras. We start be reviewing some of the -- often confusing -- nomenclature and concepts. We then look at environmental factors that impact the system performance. Finally, we present a "link budget" model that looks at light output, path losses, and camera sensitivity and noise levels. We conclude with some recommendations on ways to improve the performance of underwater imaging systems.**

Keywords*— *Underwater Lighting, Image Signal to Noise Ratio, Lux, Lumen, Chromaticity, Illumination, CRI, Color Rendering Index, lumen, lux.

I. Introduction

The basic requirements for an underwater imaging system are quite intuitive: there must be a bright enough light source to illuminate the target scene well enough for a camera to produce an acceptable image.

Having stated the obvious, however, leads us to the purpose of this paper: understanding and specifying lights and cameras for underwater applications. This can be a surprisingly complex endeavor. Naturally, "brightness" and "color", for example, are important parameters. However, these parameters can be quite difficult to quantify. Color, for example, is more than just the frequency of light. The relative intensity of the individual spectral components also has a significant effect on the perception of color. This is particularly relevant in underwater work where the attenuation varies dramatically as a function of the wavelengths present in the source lighting (Figure 1). A quantifiable metric of a lighting fixtures output can also be complicated by the multitude of varying unit references for light output measurements such as candela, lumens, lux, CRI (Color Rendering Index), etc.

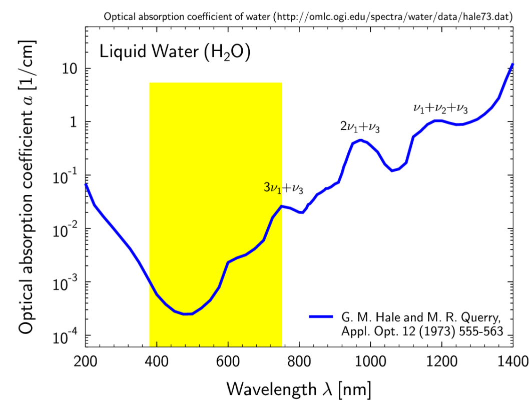

Fig. 1: Absorption Spectrum of Water

As with lighting, it would seem that the basic parameters for cameras are intuitively obvious. Two key parameters are the sensitivity and the resolution. However, while these are conceptually straight forward they only give an approximation of the image quality. Modern digital systems have added several additional factors that must be considered. One is the signal-to-noise ratio in the image. Another is the somewhat ambiguous "processing gain". For example, the built in signal processing seen in modern cameras might provide outstanding low light image quality, but this is only if both the camera and the scene remain stationary.

II. Background

For thoroughness of the discussion it is quite helpful to review some basic metrics and their relevance to the discussion.

Key Lighting Metrics

Illumination: Illumination is a general term that refers to "lighting" a target scene. It is often associated with the *luminous flux* (lux) per unit area.

Radiance and *Irradiance*: radiance refers to the energy emitted by the light source. The common metric for this is Watts -- as in "50 Watt light bulb". For a variety of reasons, some of

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which are discussed below, units of measure other than the Watt are often preferred for modern lights. Irradiance refers to the energy that is incident to the target scene.

Light Intensity: A generic term for which the meaning is context sensitive. Generally, when used with respect to underwater optical imaging, the term means luminous intensity (see *lumens* and *lux*).

Candela (cd): Classically, the candela represents the amount of light generated by a standardized candle. A more formal and modern definition is: "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian."

Lumen (luminous flux, lm): The lumen provides a measure of the total quantity of light available from a light source. Formally, the lumen is defined in relation to the candela: 1 lm = 1cd · sr (steradian). This is a useful measure of how well a light can light up an *area*. In general, the more lumens, the "brighter" the light. However, it must always be remembered that lumens provide a measure of the total light available – not the light in any particular direction.

Lux (lx): The lux generally provides a more useful measure of how bright a light is when viewed from a particular orientation. The lux is defined as 1 lm per square meter of area.

Essentially, the lumen can be thought of, in this context, as a measure of the overall brightness of the light. The lux provides a "point-source" measure of the brightness of a light. The significance is illustrated when we consider the difference between a floodlight and a spotlight. For example, consider a floodlight and a spotlight, both having an output of 1000 lumens. Each light can have a very different effect when lighting a scene. The spot light will light the scene more brightly than will a flood light – though the spotlights light will be concentrated over a smaller area. Both measures, the lux and the lumen, are important when specifying under water lighting. Strictly comparing two lights using only lux specifications can also be misleading. Just as in the case above, two lights with the same lux specifications may have very different effects when lighting a scene depending upon the area that needs to be illuminated.

Chromaticity: Chromaticity refers to color in such a way that the luminance is not a factor.

Color Rendering Index: The color rendering index gives us a method of quantitatively comparing a light sources ability to show colors relative to a reference sources ability to show colors. A value of 100 means that light should be able to show colors just as the reference source would. Typically the reference source is either the sun or an ideal black body radiator.

From a practical perspective, for underwater optical imaging we are generally interested in the lumens and the CRI metrics of a light source.

Key Camera Metrics

Sensitivity: The sensitivity of a camera will typically be specified in lux. Basically, the lower the lux number required for a camera to produce an image, the more sensitive the camera. While sensitivity seems like a metric that is well defined, the reality is that it is hard to pin down. The difficulty lies in the *quality* of the image that is produced for a given amount of illumination.

Image Signal to Noise Ratio: Due to the somewhat subjective nature of the sensitivity metric in cameras, many vendors will also specify the *signal to noise ratio* (SNR). The detail of how the SNR of a camera is calculated can vary. However, in general the process is the same: multiple images are taken under unchanging conditions. The difference between the images is calculated. From this the variance is computed and the result s the SNR.

Resolution: Strictly speaking, the resolution of a camera is not directly related to a cameras ability to capture an image at a given light level. However, in practice the resolution is often important in determining overall image quality, and therefore it plays a role in the perceived quality of an image.

III. THE LINK BUDGET CONCEPT

In communications work it is common to think in terms of a link budget. The basic concept is this: given a receiver of sensitivity *x* how much power must a transmitter radiate to deliver a signal of acceptable signal to noise ratio (SNR) to the receiver? The link budget includes factors such as the passive gain provided antennas, processing gains from symbol coding, losses due to things like water in the air, inherent losses due to spreading, etc. There is, of course, much more to a link budget calculation in a modern communications system. However, this simple description is adequate to set the stage for similar methodology in working with underwater imaging systems.

The process may begin with specifying the sensitivity of the camera and an acceptable SNR. With this information we can then ask ourselves: what light level, in lumens, must we specify for our light source?

From there, the process of building a link budget begins by first approximating the losses due to just the geometry of the system. See Figure 2.

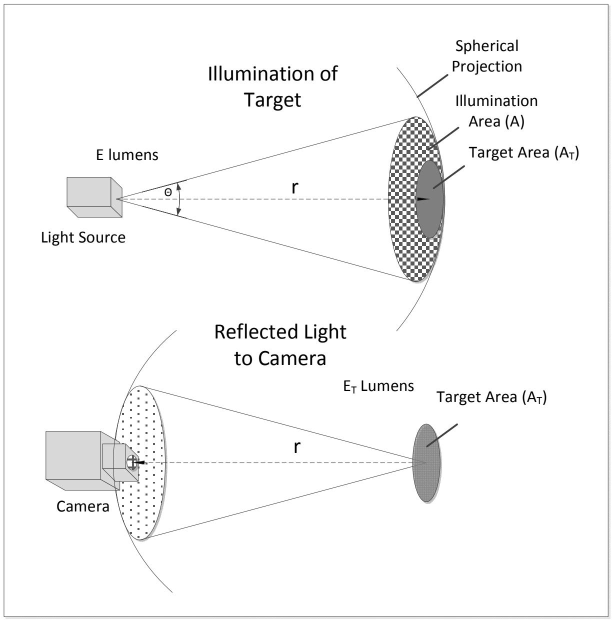

Fig. 2: Initial Lighting Geometry

For example, let's assume our camera produces an acceptable SNR when it receives 0.1 lux of light. Further let's assume our light source produces a uniform intensity beam over an angle, Θ, of 0.5 steradian (roughly 30˚). The radiance of the source is given as *E* lumens. The area illuminated by such a beam is given by:

$$A = \Theta r^2$$

where *r* is the distance from our light to the target scene. The irradiance of our target then is:

$$E_T = E/A$$
$$= E/\Theta r^2$$

This is our "spreading loss" due to light energy spreading out as it propagates. We must now calculate how much energy the target scene will return to the camera. For simplicity, we will assume our target is Lambertian – an ideal diffusely reflecting surface. We will also assume that the light from the target scene can be treated as coming from a point source. The light from the scene is the light intensity, E_T, multiplied by the area of the target (A_T).

The intensity of the light returned to the camera from the target will decrease by the inverse square law. Assuming the camera is co-located with the light source, the light delivered to the camera from the target scene is:

$$E= A_T E_T/r^2$$

Solving for E:

$$E = E_T \Theta r^4$$

Thus to provide 0.1 lux to the camera our light source would we need to provide:

$$(0.1)(0.5)(10^4)=500 \text{ lumens}$$

This, of course, neglects many other losses. In Figure 3, we identify additional losses that need to be accounted for in the link budget. The first, and the most straight-forward variable, is the absorption loss due to water.

As noted earlier, the absorption of light in water is dependent upon the wave length of the light. With this qualification, the loss of light due to absorption is generally given as:

$$E(l) = Ee^{-\alpha l}$$

Where α is the loss coefficient and *l* is the path length [2]. Generally, α will consist of two types of losses: absorption and scattering. Various sources give roughly similar values for various under water conditions [4]. However, scattering deserves a bit of attention as it can be further broken down to two types of scattering: back scatter and forward scatter. Depending up the relative position of the light and the camera, scattering not only reduces the amount of light reaching the target, it may also increase the light noise to the camera. Thus it will have the effect of decreasing the signal-to-noise ratio of system. Effectively, this noise is added to the SNR of an imager.

Putting all of this together leads to a basic link budget model as shown in Figure 3. This model illustrates many of the concepts that under water imaging operators know instinctively. For example, if the light source and the camera are separate, the quality of the SNR of the system (the quality of the image) is improved by moving the light closer to the target scene (decreasing d_0 in Figure 3). This increases the light on the target by minimizing absorption and scattering losses. However, it also reduces the scattered light that finds its way to the camera, thus minimizing the decrease in SNR that would result if this light were to enter the sensor. In a similar fashion, moving the camera closer to the target scene minimizes the path loss of the light, thus effectively increasing the amount of light at the sensor.

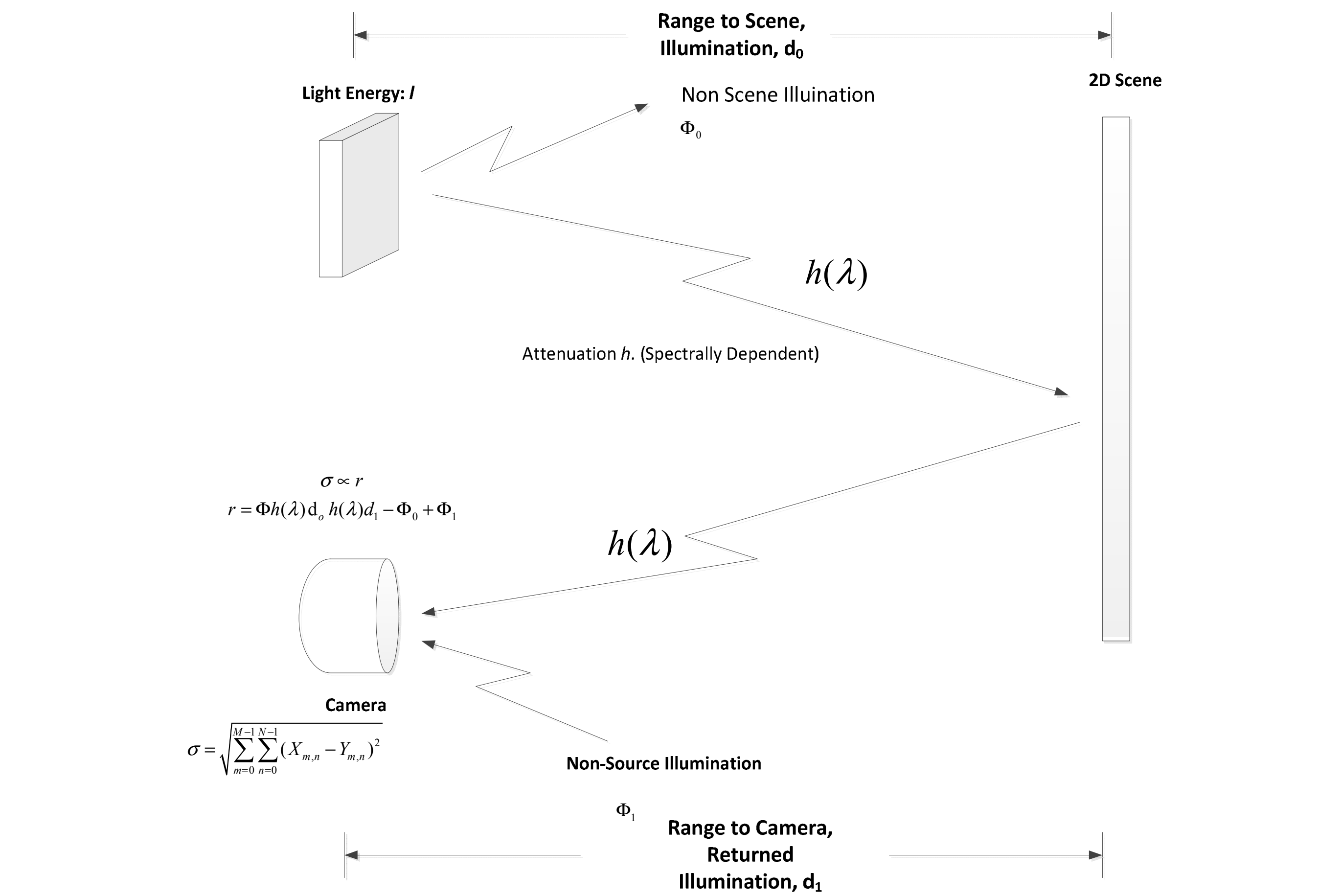

Fig. 3: Link Budget Model

IV. CONCLUSIONS AND FUTURE WORK

There is a large and well established body of work on topics such as light propagation underwater. However, there is little literature that directly address a methodology for developing a system specification that address questions such as the required light output of a source, the nature of that light, and the camera characteristic that are required for a system operating under a given set of conditions. In this absence, system designers are forced to rely on intuition and empirical data gathered from experience. While there is no substitute for the value that experience brings to any effort, a quantitative approach to a systems specification can help reduce the time and cost involved in developing a system.

The model presented in this paper can be legitimately criticized for its simplifying assumptions. However, it does provide a point of departure for working through the requirements for an underwater imaging system. In the future we plan on working further to develop the quantitative metrics that will provide both a set of coefficients for a variety of conditions and a more robust model for determining the requirements of the individual components in meeting the overall performance goal of an underwater imaging system.

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