ABSTRACT

A resurgence is occurring in the area of underwater laser communications. While acoustic systems are currently the more mature technology, they are ultimately band-limited to sub-MHz type data rates due to the frequency dependent absorption of acoustic energies in water. Advances in fiber optic and free space links have shown promise for optical links to provide data rates in excess of a gigabit per second. It is not surprising then, that laser links are being considered for Naval applications involving high bandwidth communications underwater.

A major challenge in implementing optical links underwater arises from the spatial dispersion of photons due to scattering. Spatial spreading of the optical beam reduces the photon density at the receiver position. As such, optical links are only expected to be of greatest utility in links <100m. Nonetheless, it appears that end users may accept limited link range in exchange for the gain in information bandwidth that optical links may provide. Additionally, researchers continue to study how spatial spreading affects the time encoded portion of the transmitted optical signal. Temporal dispersion arising from multiple scattering events may result in inter-symbol interference (ISI), further limiting link range and/or capacity.

Researchers at NAVAIR in Patuxent River MD are currently investigating both the spatial and temporal effects of scattering on a laser link in turbid underwater environments. These links utilize an intensity modulated beam to implement coherent digital modulation schemes such as PSK and QAM. Through both modeling and experiment, the underwater channel is characterized both spatially and temporally. Results are providing insight to system requirements of link range, pointing accuracy, photo-receiver requirements, modulation frequency, and optimal modulation format.

Table 1 – Typical bandwidths of an acoustic system with range.

| Range      | Data Rate (kbps) |
|------------|------------------|
| Very Long  | > 100            |
| Long       | 10-100           |
| Medium     | 1-10             |
| Short      | 0.1-1            |
| Very Short | < 0.1            |

MOTIVATION

The challenges of underwater communication while at speed and depth are widely known in Naval communities. Despite rapid growth in RF wireless technologies, underwater applications were relatively unaffected, as radio frequencies do not penetrate the sea surface and are highly absorbed by water. RF communication from land to submarines using the ELF band does exist, but it is terribly inefficient due to the large ground stations required and results in dreadfully low bandwidths compared to today’s communication standards.

Acoustic techniques on the other hand have enjoyed large success in providing moderate data rates underwater [1-3]. A summary of acoustic link performance is included in Table 1. While sound waves generally propagate well though seawater, the acoustic channel is highly frequency dependent and can experience significant multipath delays. As such, even at short ranges, the acoustic channel is limited to sub-Mbps data rates.

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Optics presents yet another alternative for establishing wireless underwater links. With the success of fiber optic communications, and the growing applications and success of free space optical links, optical technologies have proven their ability to provide large information bandwidths. Furthermore, seawater
exhibits a “window” of decreased absorption in the blue/green region of the visible spectrum where a number of off-the-shelf laser sources are available. Using lasers for undersea communications is not a new idea, with much of the initial interest in this area arising in the 1970’s and 1980’s [4-5]. The majority of the work during this time examined the feasibility of communicating with submarines from aircraft or satellites. This application presented a number of critical challenges since it required the laser signal to propagate long distances through the atmosphere, through the air/water interface, and finally through the challenging underwater environment. This required high power, high repetition rate blue/green sources that were not available at the time. While new technologies for the required laser sources stand poised to revisit this application of “through the surface” communication, a wealth of new applications have arisen for horizontal links between platforms underwater. With the advent of autonomous data collection nodes, giant leaps in unmanned vehicle technology, and increased need for submarine stealth, short range (<100m) high speed (>1Mbps) horizontal links are an attractive feature to many of these new applications.

In the ideal case of clear, open ocean waters, it is not unreasonable to predict that optical links might provide upwards of ~Gbps data rates at ~100m. However, in practice even a small amount of scattering can cause degradation to both range and bandwidth. In turbid harbor environments the issue is compounded, as a highly directional laser beam now becomes largely diffuse due to multiple scattering caused by particulates in the channel. Therefore, in order to accurately predict the performance bounds of the underwater optical link, the underwater channel must be characterized from both a spatial and temporal perspective. This work summarizes both experimental and modeling efforts that are ongoing at the Naval Air Warfare Center (NAVAIR) at Patuxent River MD which attempt to gain clearer insight as to the spatial and temporal effects of scattering on the underwater optical link.

**SPATIAL EFFECTS**

We begin with a simple link budget equation. The received power at time \( t \), at a receiver \( z \) meters away from the laser source can be described as,

\[
P_r(t,z) = P_T(t) G_T L_w(t,z) G_R
\]

where \( P_T(t) \) is the transmitted optical signal that is encoded with information, \( G_T \) is the transmitter gain that includes the beam aperture and divergence, \( L_w(t,z) \) is the loss due to propagating \( z \) meters through the water column, and \( G_R \) is the receiver gain that includes the receiver aperture and field of view. Of particular interest is the channel loss term, \( L_w(t,z) \). In this section, we will deal with the non-time dependent component of this term, \( L_w(z) \).

It is well known in the study of ocean optics that two fundamental processes affect light in water: absorption and scattering. Absorption is an irreversible thermal process where photon energy is lost due to interaction of light with water molecules and other particulates. Scattering is a process whereby a photon’s path is altered upon interaction with particulate matter. Absorption and scattering are wavelength dependent, and often denoted by the coefficients \( a(\lambda) \) and \( b(\lambda) \) respectively. Together, they form the attenuation coefficient \( c(\lambda) = a(\lambda) + b(\lambda) \). The beam attenuation coefficient is used to describe the total attenuation of non-scattered light as,

\[
L_w(z)_{NS} = \exp(-cz)
\]  

Typical values for the attenuation coefficient at blue-green wavelengths are shown in Table 2 [6]. It is also common to describe water clarity by the product \( c*z \) in equation 2, commonly known as the attenuation length.

It is important to point out that Eqn. 2 describes the attenuation only when the transmitter and receiver are precisely aligned, and that the receiver aperture and FOV are such that only ballistic (non-scattered) light is collected. From a communications link perspective, this situation may rarely occur. Depending on water turbidity, transmitter/receiver pointing accuracy, receiver field of view (FOV), and other factors, the receiver is likely to collect both scattered and non-scattered light. In fact, under some cases of extreme turbidity and/or loose pointing it is reasonable to assume that a receiver may collect only scattered photons. In this case, eqn. 2 does not hold.

| Water Type            | \( a \) (1/m) | \( b \) (1/m) | \( c \) (1/m) |
|-----------------------|---------------|---------------|---------------|
| Pure sea water        | .0405         | .0025         | .043          |
| Clean ocean           | .114          | .037          | .151          |
| Coastal ocean         | .179          | .219          | .298          |
| Turbid harbor         | .266          | 1.824         | 2.19          |

Table 2 – Absorption, scattering, and attenuation coefficient values for typical ocean water types at blue-green wavelengths. Table courtesy of [6].
To more accurately describe the attenuation of scattered light, we must additionally examine the angular properties of scattering. Fortunately, such studies have been ongoing in underwater optics for many decades. The volume scattering function (VSF) describes the angular distribution of photons in scattering conditions. Figure 1 shows the VSF's of representative ocean waters under single scattering conditions ($cz \leq 1$) as measured by Petzold [7]. Note that the VSF of ocean waters is strongly peaked in the forward direction, a quality that is potentially quite beneficial from the perspective of the communications link geometry.

In this work, we will study the beam spread function (BSF) that describes the total scattering profile of a collimated transmit laser beam as a function of range and water turbidity. Note that the BSF includes non-scattered, single scattered, and multiply scattered light, thereby fully describing the total spatial profile of the optical signal. Figure 2 shows a graphical representation of the BSF in the communications link scenario. A source is located at $z=z_{src}$ and directed to a receiver $z$ meters away at $z=z_{rec}$. Assuming axial symmetry, the BSF can be described as the intensity as a function of distance $r$ meters from the main beam axis on a plane located at $z_{rec}$.

A computer model has been developed to examine the BSF [8-9]. This analytical model computes a solution to the rather complex radiative transport equation (RTE) and requires little computation time (on the order of seconds) with the aid of the Small Angle Approximation (SAA) [8-10].

To validate this mode, laboratory experiments were performed in a small water tank (1m x 1m x 3.66m) with windows on opposite ends. The source is a continuous wave laser beam ($\lambda=532$nm). A photomultiplier tube (PMT) is used as the receiver. The receiver is mounted on a motorized stage such that it can be scanned laterally in and out of alignment of the main beam. Traditionally, Maalox antacid is used as a laboratory scattering agent, as it has similar scattering properties of real ocean waters [7],[11]. Figure 3 shows the experimental setup, and more details are found in [12].

Figure 4 shows the results of the model and experiment, normalized to the intensity seen when the transmitter and receiver are precisely aligned ($r=0$). Strong agreement is shown for various water turbidities ($c=0.275/m-3.2/m$) and over a moderate lateral distance ($0<r<0.4m$). The results confirm our intuition based on the properties of the VSF's of ocean waters seen in figure 1 in that scattering is highly concentrated in the near forward direction. In clear waters, the transmitted beam remains highly directional, as the intensity falls off rapidly when the transmitter and receiver are even slightly misaligned. As the water becomes more turbid, photons are scattered out of the main beam into the near forward angles and the profile approaches that of a diffuse source.

While strong agreement between model and experiment has been shown for various turbidities at short ranges (<5m), it is still important to continue investigation of the BSF at longer ranges where optical links are likely to be of the most use. The authors are currently performing both modeling and experiments to further understand how the BSF scales with range. Results are expected to be reported on soon.
In the meantime, we can make some observations about how spatial spreading of a collimated beam impacts the communications link in terms of range, water clarity, and transmitter/receiver pointing, acquisition, and tracking (PAT). Previously, we asserted that loss term, $L_w(z)$, in equation 2 describes the attenuation of light that has not been scattered or absorbed, and is valid only when the transmitter and receiver are finely aligned. Even under strict PAT requirements, if there is significant scattering, then multiply scattered photons may scatter back into the receiver collection aperture. The amount of scattered photons that are collected will depend on the receiver field of view (FOV) and PAT requirements. To account for the collection of scattered photons, we can define a system attenuation coefficient,

$$k_{sys} = a + (1 - n)b$$

(2)

where $n$ is a percentage of scattered light collected relative to the total amount of scattered light. When no scattered light is collected, $n=0$ and $k_{sys} = c$. At the other extreme when all the scattered light is collected, $n=1$ and $k_{sys} = a$. The actual value of the system attenuation coefficient is related not only to water optical properties, but also to link factors such as receiver FOV, transmitter beam divergence, and transmitter/receiver PAT.

To illustrate this point, we use the computer model to examine the received intensity as a function of range for various pointing angles. A laser source power of $3W$ (34.8dBm) is used by the model, as lasers at this power are readily available off-the-shelf. The model also assumes a wide open FOV (FOV=180degrees). The resulting intensity output from the model is then integrated over an 8mm aperture. This is the aperture size of the Hamamatsu R7400U-20 PMT which is a popular off-the-shelf photodetector often used in underwater communications and imaging systems. This PMT has a dark current level of ~0.5pW (-93dBm), and we will use this as our theoretical bit detection threshold. An actual link is likely to be limited by other noise sources. Furthermore, the modulation scheme will impose its own requirements on the minimum detection level for a given acceptable probability of bit error. Until a complete noise analysis can be done for the receiver, we will use the dark current limit to illustrate the potential implication of scattered light attenuation on link performance.

Figure 5 shows the received optical power versus link range for various receiver positions ($0m < r < 10m$) at $c=0.275/m$. Note that the on-axis light attenuates by equation 2 up to $z=75m$ ($cz~20$). At higher attenuation lengths, the signal attenuates as $\exp(-k_{sys}z)$ where $k_{sys}=a+0.166b$ ($n=0.84$). This is because the majority of light has undergone small angle forward scattering on its way to the receiver. Note that in the dark current limit, equation 2 would underestimate the link range by a factor of two. This underestimation is greater for larger values of the attenuation coefficient. The reader is referred to [12] for those results. Finally, we note that for $z < 75m$, equation 2 also fails to correctly describe the attenuation for any of the off-axis receiver positions. It is therefore obvious that BSF models such as the one described here would prove to be an essential tool in developing link budgets since they provide a more complete description of the effect of scattering on an underwater optical link.
Figure 5. Received optical power vs. link range for various transmitter/receiver pointing accuracies with $c=0.275/m$. Extreme values of $k_{sys}=c$ and $k_{sys}=a$ are shown as dotted lines. The link range for a dark current limited system is underestimated by a factor of 2 when modeling optical loss by only the attenuation coefficient.

TEMPORAL EFFECTS

An analytical model is currently being developed to compute the time-dependent loss term, $L_w(t,z)$ in equation 1. In the meantime, the authors have been performing experiments to characterize the time dependency of forward scattered light. There has been, and continues to be, a large amount of investigation of the transmission of short optical pulses through a scattering underwater environment [13-16]. The work presented here is unique in that it encodes information by intensity modulating a continuous-wave laser source at frequencies between 10-100MHz. The intensity modulation can be used to implement digital modulation schemes popular in RF wireless applications like phase shift keying (PSK) or quadrature amplitude modulation (QAM).

Before we discuss the implementation of these schemes, it is important to first understand how scattering affects the modulated optical signal. Previously, we examined how the optical carrier is attenuated based on water turbidity, pointing accuracy, and other factors. Here, we wish to determine how these same variables affect the RF sub-carrier, namely the modulation depth. For PSK schemes, the effect of scattering on the received phase is also important.

Figure 6 shows the experimental setup of the temporal investigation in a small 1m x 1m x 3.66m water tank. The procedure is similar to the BSF measurements in the previous section. On one end of the tank, a laser beam (532nm) intensity modulated at 70MHz enters the tank. At the opposite end, a PMT is placed on a rail such that it can be moved laterally out of alignment with the main beam ($0<r<30cm$).

Modulation depth as a function of receiver position with increasing water turbidity is measured. Figure 7 shows that for waters with attenuation coefficients between $0.8/m<c<24/m$, there is no decrease in modulation depth even when the receiver is positioned off-axis ($r=0.4m$). One reason may be due to the relationship between modulation wavelength and physical link range. The size of the small water tank ($z=3.66$) is approximately equal to the 70Mhz modulation wavelength ($\lambda=3.22m$ in water). Over a larger physical range, or wider pointing mismatch, a loss of modulation depth may be observed. Experiments in a larger circular water tank (diameter =7.72m) are currently being performed to further evaluate the effect of longer ranges. Additionally, the receiver used in this measurement had a FOV=18 degrees. At longer ranges and/or wider transmitter/receiver pointing mismatches, a larger FOV may collect more scattered light, thereby reducing modulation depth.

Additional studies on the modulation phase were performed by the authors in [17]. It was found that drastic increases in water turbidity did result in a phase change in the modulated RF-subcarrier. This change in phase however only occurred with changes in water turbidity, and was fairly constant at a single turbidity versus lateral receiver distance. This suggests that while photons are certainly scattering along the channel, all of the light collected by the receiver’s finite FOV have scattered approximately the same amount. Therefore, we would expect intersymbol interference (ISI) due to multipath scattering to be minimal for PSK and QAM schemes. This is a significant result, especially when compared to acoustic communication systems that may exhibit ISI over tens to hundreds of bit periods due to multipath reflections. The results here suggest that signal-to-noise loss is more likely to be due to
absorption and scattering losses rather than modulation loss or multipath interference (temporal losses), at least at these short ranges.

In [18], the authors studied the impact of water turbidity on PSK and QAM schemes. Some results are shown in figure 8 at \( c\approx 2.3/m \). Measurements were made in the same small water tank. A 70MHz carrier frequency was used, and the symbol rate was 1MS/s. As discovered previously, scattering had little effect on the amplitude and phase of the RF-subcarrier. Error free transmission can be achieved provided that the transmitted optical power is high enough to overcome the losses due to absorption and losses due to photons that get scattered outside the receiver FOV. With the current laboratory hardware used in this study, 5Mbps was achievable with 32-QAM signaling. This data rate was limited by the laboratory equipment, not the environment.

**CONCLUSIONS AND FUTURE WORK**

Optical links are a viable option for high bandwidth wireless links underwater. Because of the challenging underwater environment, laser links will have the most utility in short range scenarios (<100m). We have shown that in characterizing the performance of these links, both the spatial and temporal effects of scattering need to be considered. First, we have seen that computing the attenuation of the optical signal by \( \exp(-cz) \) is insufficient. For one, it fails to describe attenuation when the receiver is not precisely aligned with the receiver. Furthermore, it fails to describe the attenuation of light that has scattered on its path to the receiver. We have shown that a theoretical model to describe the BSF is an essential tool for overcoming this in that it fully describes the spatial profile of the scattered beam. Additionally, studies on an intensity modulated optical signal have been performed. At short ranges (<5m) there is no loss of modulation depth with water turbidity (up to 88 attenuation lengths) or moderate transmitter/receiver pointing mismatch. Such results have made the implementation of PSK and QAM schemes possible for the underwater scenario.

In both cases, it is necessary to continue this study at longer ranges. First, we wish to determine how the BSF scales at longer ranges. Second, a longer physical range may allow the time encoded information signal to become decorrelated due to undergoing more scattering events. In both cases additional link factors such as transmitted power, modulation frequency, receiver FOV, receiver sensitivity, transmitter/receiver pointing accuracy, link range, and others will all play important roles in characterizing the link. Experiments and modeling that take into account these factors continue and will be reported on in the future.

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