UNDER WATER COMMUNICATION

1.INTRODUCTION

The future tactical ocean environment will be increasingly complicated. In addition to traditional communication links there will be a proliferation of unmanned vehicles in space, in the air, on the surface, and underwater. Above the air/water interface wireless radio frequency communications will continue to provide the majority of communication channels.Underwater, where radio waves do not propagate, acoustic methods will continue to be used.However, while there have been substantial advances in acoustic underwater communications, acoustics will be hard pressed to provide sufficient bandwidth to multiple platforms at the same time. Acoustic methods will also continue to have difficulty penetrating the water/air interface. This suggests that high bandwidth, short range underwater optical communications have high potential to augment acoustic communication methods.

The variations in the optical properties of ocean water lead to interesting problems when considering the feasibility and reliability of underwater optical links. Radio waves do not propagate underwater, however with the proliferation of unmanned autonomous vehicles the need to communicate large amounts of data is quickly increasing. Making physical connections underwater to transfer data is often impractical operationally or technically hard to do. Traditionally most underwater communication systems have been acoustic and relatively low bandwidth. However, the development of high brightness blue/green LED sources, and laser diodes suggest that high speed optical links can be viable for short range applications. Underwater systems also have severe power, and size constraints compared to land or air based systems. Underwater vehicles also encounter a wide range of optical environments. In shallow water the effects of absorption by organic matter and scattering by inorganic particulates can be severe compared to deep ocean water. Where the system operates in the water column can also have strong influence. Near the sea floor, ocean currents and silt can play a factor, while in the middle of the water column the medium may be considered more homogeneous, but with its optical properties varying as a function of depth. Near the surface, sunlight can provide a strong background signal that needs to be filtered, and the amount of wave action can have significant effects.In this thesis the use of free space optical links will be investigated for underwater applications. With the use of MathCAD, optical link budgets for three different scenarios are considered:

- A blue/green LED based, bottom moored buoy system operating in relatively shallow water.
- A blue/green laser based system operating in deep clear ocean water with unlimited power and size constraints.
- A power and size constrained, diode laser system suitable for small unmanned underwater vehicle operation.

Inputs into the link budget include: light source type, wavelength, optical power, beam divergence, ocean water optical parameters based on depth, geographic location and time of day, and photodetector type. As a point of comparison, the relative merits of these systems are compared to a conventional acoustic communications links.

A secondary focus of the thesis was to construct light emitting diode based links. The choice of using LEDs instead of Lasers was largely economic, however in the underwater environment can be very challenging optically and many of the advantages that lasers have in terms of beam quality can be rapidly degraded by scattering and turbulence.

2.Free Space Optics Concepts

Free-space optics (FSO) is a line-of-sight (LOS) link that utilizes the use of lasers or light emitting diodes, LEDs, to make optical connections that can send/receive data nformation, voice, and video through free space. FSO also has attractive characteristics of dense spatial reuse, low power usage per transmitted bit, and relatively high bandwidth. FSO is license-free and offers easy to deploy, fast, high bandwidth connections. Moreover, the optical spectrum is not regulated by the FCC allowing the use of large amounts of unlicensed bandwidth. Due to the large investment in traditional fiber based optical communications networks, LED's, lasers, photodetectors are available today cheaply and in large volumes. A free space link requires a light source, modulation/demodulation device, and transmitting and receiving telescopes. For moving targets, the transmitter and receiver are placed on gimbal system with feedback controls1 . Instead of propagating through silica glass, as with optical fiber, the light travels through free space.

The main disadvantage of FSO networks is that the transmission medium is uncontrolled. The effects of atmospheric distortions, scintillation, weather and attenuation can only be minimized or compensated by the transmitter/receiver hardware. Free-space optics above and below water have similar issues that need to be accommodated when building a system. Issues that are problematic for FSO networks and impact the communication link reliability and data rate are listed in Table 2.1.

Solar Interference	Sunlight can be picked up by the detector adding white and shot noise.
Alignment Issues	LOS beams are very narrow which causes major issues with alignment. Tracking is required for moving links and even on some stationary links.
Scintillation & Turbulence	Variation of the refractive index along the propagation path caused by temperature and density variations leading to large variations in signal strength on the receiver photodetector

Absorption	Loss of Light intensity due to wavelength dependent particle absorption in the medium
Scattering	Mie Scattering – Light being redirected by particle roughly same size as than the propagating wavelength Rayleigh Scattering – Light being redirected by particle smaller than the wavelength Multi-Path Scattering/Multi-Path dispersion
Multi-Path dispersion	The path a photon takes is ideally a straight line, but due to scattering the photon may be redirect several times causing the light pulse to spread in time.
Physical Obstructions	Living organisms that enter into the beams path causing dropping of bit or total loss of connection

Table 2.1 Optical link variables that affect both free space and underwater mediums.

2.1Appling FSO Concepts to Seawater

The transmitter and receiver for an underwater link can be very similar to a FSO link in air, the major difference being the wavelength of operation. However, ocean water has widely varying optical properties depending on location, time of day, organic and inorganic content, as well as temporal variations such as turbulence. To construct an optical link it is important to understand these properties. The loss of optical energy while traversing the link arises from both absorption and scattering. Scattering also adversely impacts the link by introducing multipath dispersion.

3.Water Types

The physical properties of ocean water vary both geographically, from the deep blue ocean to littoral waters near land, and vertically with depth. Vertically, the amount of light that is received from the sun is used to classify the type of water. The topmost layer is called the euphotic zone and is defined by how deeply
photosynthetic life can be found. Below this zone is the dysphotic zone, sometimes as deeply as a kilometer down, but the light is too faint to support photosynthesis. From the lower boundary of this zone and extending all the way to the bottom is the aphotic zone, where no light ever passes and animals have evolved to take advantage of other sources of food7.

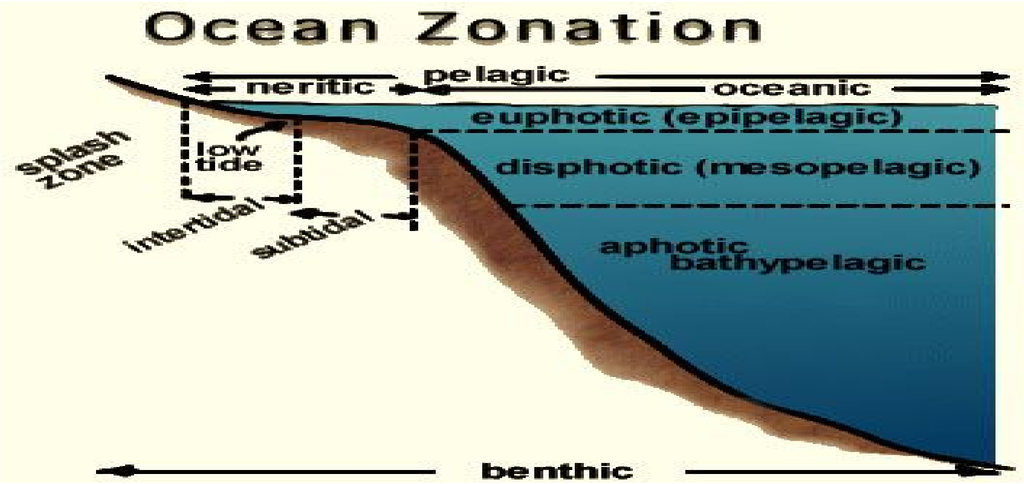

Figure 3.1: Diagram of the different oceanic zones, euphotic zone ends where 99% of the surface radiation has been absorbed, phytoplankton live and reproduce in this zone6.

Each zone has its own optical properties, which adds another degree of difficulty when constructing a link budget. A system in the euphotic zone would act different than in the aphotic zone or if it was going from zone to zone.

3.1 Attenuation Underwater

Attenuation underwater is the loss of beam intensity due to intrinsic absorption by water, dissolved impurities, organic matter and scattering from the water, and impurities including organic and inorganic particulate. The amount of attenuation changes with each Jerlov water type. Each water type also contains different levels of biomass known as[8,9]:

- Phytoplankton-unicellular plants with light absorbing chlorophylls,
- Gelbstoffe -dissolved organic compounds know as yellow substance, Other optical effects of the biomass include:
- Fluorescence -re-emission of light at a lower frequency by absorber illuminated with optical energy,
- Bioluminescence- emission of light by marine organisms.

Bioluminescence does not actually absorb light, but various species of organisms release light by there own means. The peak of the bioluminescent signals is centered on the bluegreen region and can potentially increase the noise present in the system.

3.2 Absorption by Pure Seawater

Seawater is composed of primarily H_20, which absorbs heavily towards the red spectrum. It also has dissolved salts like NaCl, $MgCl_2$, Na_2SO_4, $CaCl_2$, and KCl that absorb light at specific wavelengths[10]. As seen below, pure seawater is absorptive except around a 400nm-500nm window, the blue-green region of the visible light spectrum.

The absorption coefficient for pure seawater is the amount of absorption per meter of sea water. However, the majority of the attenuation is due to other mechanisms such as absorption by chlorophylls and humic acids, and scattering from particulate.

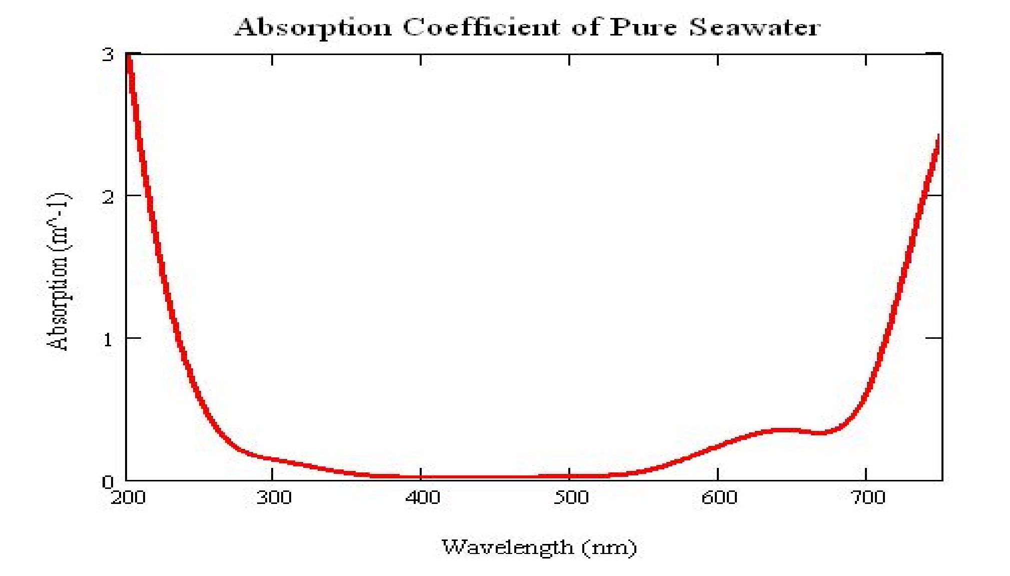

Figure 3.2: The absorption coefficient (m-1) is shown as a function of wavelength (nm) for pure seawater8,9.

3.3 Suspended Particulate and Colored Dissolved Organic Materials (CDOM)

Variations in the spectral absorption of water result from the variations in the concentrations and chemical compositions of the material substances distrusted within the water column. These absorbing materials may be present in seawater whether in suspended particulates, such as pigment-bearing phytoplankton or CDOM.

3.4Phytoplankton – Chlorophyll-a

Phytoplankton, derived from phyto, meaning plant and planktos, meaning wandering, is one of the most influential factors in light transmission through ocean waters. Phytoplankton live in the euphotic zone, which is the region from the surface to where only 1% of the sunlight reaches. Depending on the geographical location, time of day and season, the zone ranges in depth from 50m to about 200m in open ocean; typically it's around 100m[7]. Phytoplankton use chlorophyll-a, which absorbs mostly in the blue and red region and scatters green light to produce "food" through the process of photosynthesis[10]. As the concentration of chlorophyll-a increases, more blue and red light are absorbed, leaving the water a greenish tint.

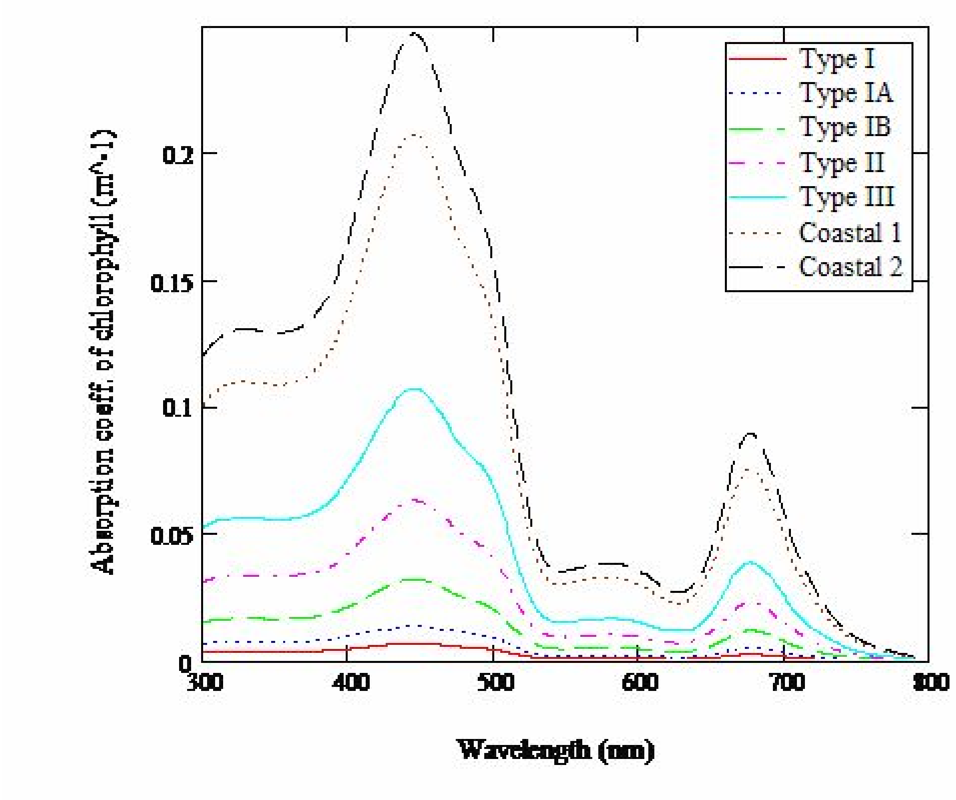

Figure 3.3: Cubic spline curve fitting of the absorption coefficient as a function of chlorophyll concentrations in the different Jerlov water types11,9,12.

Another complicated factor with phytoplankton is its distribution within the euphotic zone. Phytoplankton are not equally distributed vertically through the water column. However they have been modeled assuming a Gaussian style distribution. The formula for the depth profile for chlorophyll is[13]:

3.5 Color Dissolved Organic Material

CDOM, also know as gelbstoff (German for the word “yellow”), is composed of decaying organic marine matter, which turns into humic and fulvic acids that absorb in the blue region and fluoresce at 420-450nm[17,9,18]. Because blue is absorbed leaving green and red, gelbstoff has a yellowish tint. Gelbstoff is generally present in low concentrations in oceanic waters and in higher concentrations in the coastal waters[8]. one can see that the absorption coefficient shifts as the concentration of gelbstoff changes.

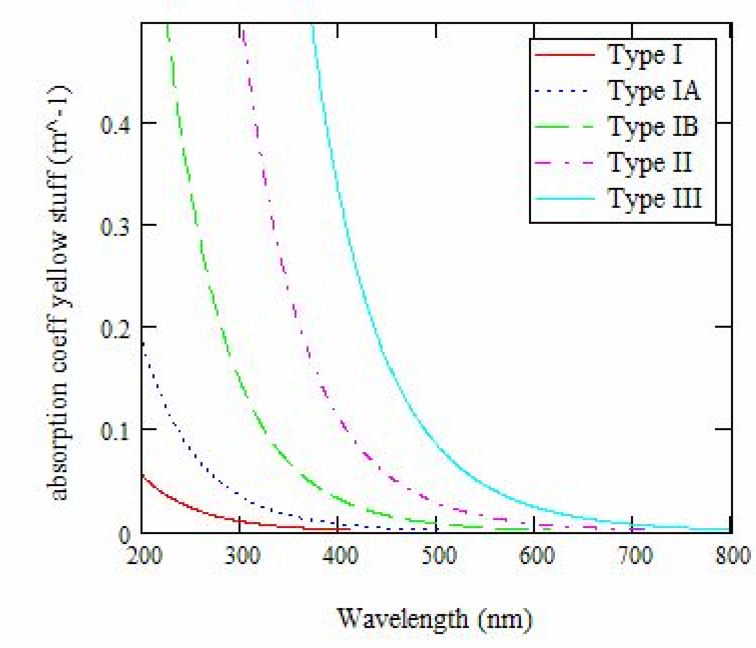

Figure 3.4:Absorption coefficient of gelbstoff (yellow substance), adapted from the one-parameter model of gelbstoff as a function of chlorophyll[19,18]

3.6 Scattering Underwater

Scattering can be thought of as the redirection of incident photons into new directions so it prevents the forward on-axis transmission of photons, thereby casting a shadow. So a beam will "spread" in diameter or loose light intensity.

3.7 Scattering by Pure Seawater

Because of the inherent scattering of molecules, and of the salts dissolved in thewater, a certain amount of initial scattering has to be taken into account before calculating thetotal scattering coefficient. Below is a graph of the scattering coefficient of pure seawater as a function of wavelength.

This type of scattering is Raleigh scattering, with strong wavelength dependence seen with the increased scattering at shorter wavelengths. When a photon is redirected after a scattering event, from the original path by an angle difference of ϕ, in degrees, the molecular scattering phase function can be represented by the following equation interpolated from data in reference20:

$\beta(\phi)$=**0.06225(1+0.835cos2(ϕ))**

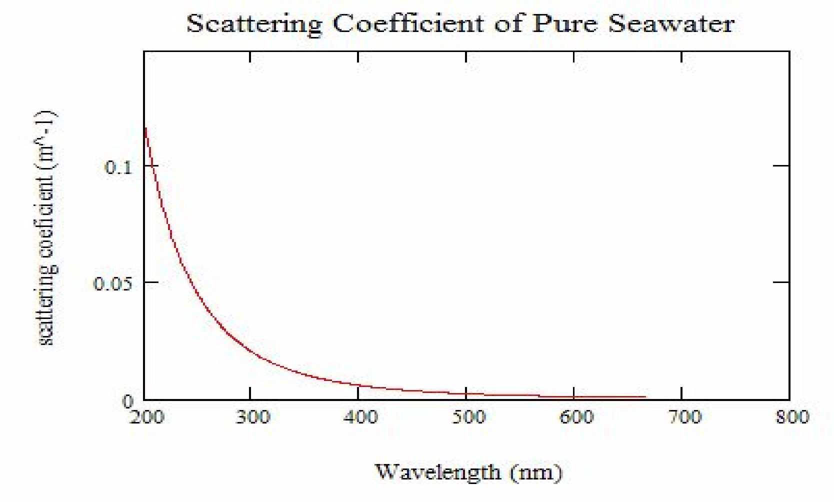

Figure 3.5: Scattering coefficient (m-1) of pure seawater as a function of wavelength (nm)[9].

The magnitude of $\beta_w(\phi)$, represents the probability that the photon scattering interaction with a water molecule will redirect the photon path direction by an angle of ϕ. The phase function is a combination of the forward scattering (angles between 0 and 90) and the backscattering (angles between 90 and 180) components. In an "isotropic" case, assumed above, the probability for forward and backward scattering are equal.

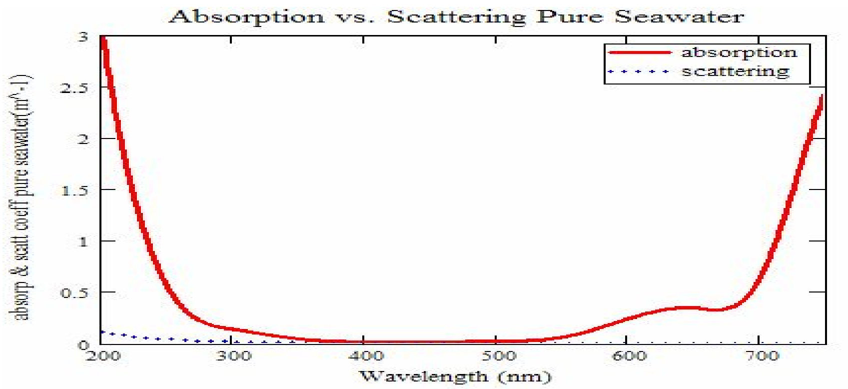

Figure 3.6 For pure seawater, the absorption coefficient is overlapped onto the scattering coefficient plot showing the dominate nature of absorption.

<u>**3.8 Scattering by Suspended Particulate**</u>

Scattering in the ocean is due to both inorganic and organic particles floating within the water column. Where in the open ocean scattering comes mainly from organic particles (phytoplankton, etc.), in the coastal waters and continental shelf, inorganic matter contributes to 40-80% of the total scattering[8]. Scattering also comes from turbulent inhomogeneities in the salinity and temperature in the water[17]. Scattering from the particulates depends on the degree of external reflection and diffraction by their geometric form, and the internal refraction and reflection from the index of refraction from the particulates[8]. The shape of the particle is usually not the dominate concern, but the size determines whether Rayleigh or Mie scatterings should be considered as the main mechanism.

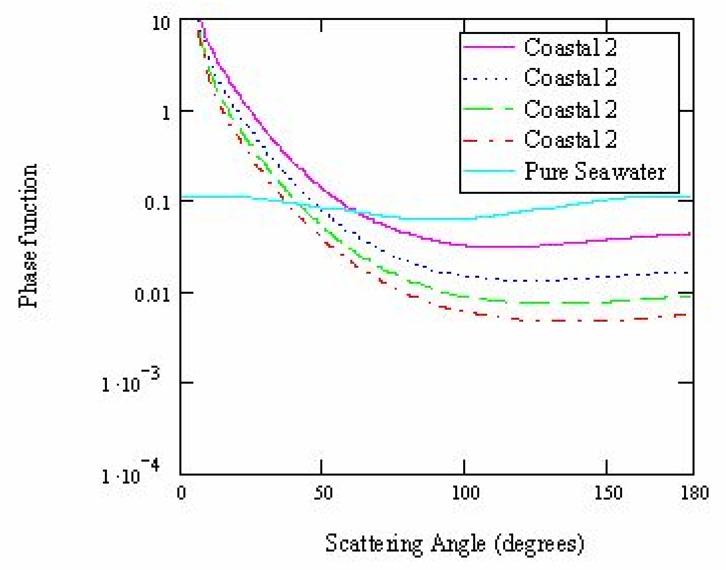

Figure 3.7: Overlap plot of the pure seawater phase function and the ocean water dominated by particle scattering as a function of wavelength (nm).

In the ocean water where particle scattering dominates, the probability of scattering in the forward direction is several magnitudes higher than the backscattering. The figure above also suggests that total angular scattering approaches a constant as the angle approaches zero, with the beam pattern that is strongly peaked in that direction. Another consequence of this is that the tolerance of transmitter and receiver pointing requirements become tighter.

3.9 Turbulence

For the purposes of this study, scintillation from turbulent water, variations of the refractive index due to variations from flow, salinity, and temperature and effects of stratified layers of water are ignored since they are considered to be less important than absorption and scattering.

The refractive index of seawater and it dependence on environmental parameters has been measured[24]. Water is relatively incompressible, however with increasing depth and pressure the refractive index increases.

The temperature dependence on the refractive index is near a maximum of 4 $_{o}$C at about 1.334 and decreases with temperature to about 1.3319 at 30 $_{o}$C. The impact of salinity is larger still with one part per thousand increase in salinity (1gr/kilogram) resulting in $1.92x10_{-4}$ increase in refractive index.

4. Link Budget

Judging the relative merits of optical communication systems can be difficult due to the wide variety of different methods that can be used to communicate. The usual method of comparing the relative merits of communication systems is to use Bit-rate Length product. This FOM has been used to discuss the evolution of communications systems, especially the fiber optic communication systems.

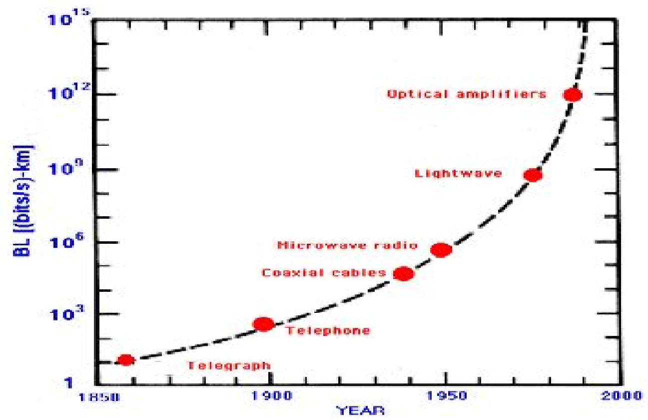

Figure 4.1: Evolution of fiber optic photonic systems expressed as Bit Rate Length Product

In the design of these optical fiber systems, one computes a link budget to determine if information can be successfully transmitted over the desired distance.

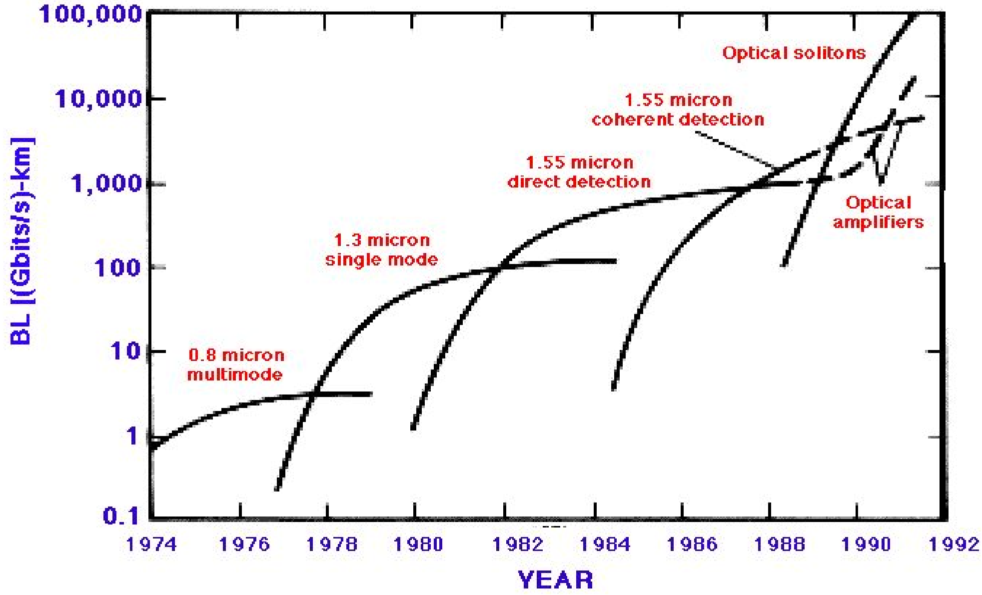

Figure 4.2:Growth of different Communication Systems Expressed as Bit Rate Length Product

Typically oneconsiders an optical power budget and a bandwidth budget. The power budget is to determine that there is sufficient signal to noise for a specific bit error rate. In fiber based optical communications systems this is typically a few hundred photons per bit, but can be less than 10 of photons per bit using special techniques.

4.1 Power Budget

Assuming a specific wavelength of operation, and a goal of a specific Bit Error Rate (BER) to construct the power budget for a simple point to point link, one should consider:

- The transmitter output power,
- Coupling efficiency of the source and receiver to the fiber,
- Attenuation or loss of optical energy due to scattering, or absorption in(dB/km)
- Losses due to fiber splices, and Receiver sensitivity typically expressed in dB (or sometimes bit-rate/mW).

- System margin, typically about 6 dB to account for system component ageing.

If the transmitter power minus the sum of the losses is greater than the sum of the receiver sensitivity plus the system margin for a given wavelength and bit error rate, the link should be successful[1].

4.2 Rise time Budget

The purpose of a rise-time budget is to ensure that the complete system is able to operate at the intended bit-rate. The rise-time characteristics of the transmitter and receiver are usually known. The allocated rise time will depend on the format used by the system, i.e. Return to Zero (RZ) or NonReturn to Zero (NRZ). With NRZ format able to accommodate Where B is the bit rate and $_{r,\max} T$ is the quadratic sum of the following: transmitter rise time, the receiver rise time, the rise-time that is induced by intermodal dispersion, and group

26 velocity dispersion caused by the fiber. The 0.35 comes from the assumption that a RC-low frequency band pass model can be used to describe the response of the system to an impulse. The dispersion, the spread of the optical pulse in time is expressed in ps/nm-km for chromatic dispersion or ps/km for modal or multipath dispersion. In single mode fibers, chromatic dispersion dominates while for multimode fiber systems the modal dispersion dominates[1].

Depending on the choice of components, the system will be either attenuation or dispersion limited as shown in the graph below. Similarly it will be important for underwater communications to consider when underwater link will be limited by multipath dispersion from scattering and when it is power limited.

In the underwater scenario the rise time due to scattering will be important at high data rates. To date there doesn’t appear to be any measured data for communication systems underwater that have measure the effects on scattering on dispersion.

4.3 Geometric Effects in Link Budget

In non-fiber based optical communications systems, such as free space optical communications in air, radio frequency wireless, or acoustic communication systems, the medium of the channel is complex with environmental changes that are unpredictable. To decouple the real environment and variability of the problem, it is useful to first consider the medium to be isotropic and infinite so the performance bounds due to the fundamental geometric effects introduced by the transmitting and receiving apertures of the systems can be computed this way the effects of environmental fluctuations on the channel can then be added to the model.

4.4 Environmental Consideration in Link Budgets

Significant efforts have been made in trying to understand what is required for a reliable link for free space optical communications in air and space. As mentioned above, the geometric effects are fairly straightforward to compute. However, transmission through the atmosphere poses special problems. In addition to water vapor and CO_2 absorption, and scattering by aerosol particles, the atmosphere has a structure that varies with altitude.

Visibility a useful way to evaluate the suitability of the atmosphere and can range from a couple of hundred meters in fog or snow to tens of kilometers in the upper atmosphere on a clear day.

5. RF Link Budget

5.1 Geometric Effects in Link Budget

Antenna and aperture theories are also typically used for RF communication systems that are static in configuration. At high frequencies, where line of sight dominates the situation, it is similar to that of the laser beam while at lower frequencies multi-path effects dominate. In mobile RF communication system, while the problem in theory is static, the receiver will sense large variations in signal intensity as it moves in the environment. In the design of a system for cellular radio communications, much of the effort is ensuring that the placement cells such that the receiver (cell phone) will always have a statistically significant probability of receiving sufficient signal to noise. The placement will be very different in an urban environment with lots of strong scattering as compared to a suburban environment where the amount of scattering is much less.

6. Acoustical Link Budget

6.1 Geometric Effects in Link Budget

Similarly in acoustic communications, the deep water environment will be different than the shallow water environment, purely from the geometric effects of multiple reflections from the bottom and surface.

For acoustic single transducers the emitter can be considered omnidirectional, although there shadowing effects that attenuate the signal. Using phase delay techniques multiple transducers can be used for acoustic beam forming, and the energy emitted or collected in a specified direction. For small platforms typically only a single transducer will be used.

6.2 Environmental Consideration in Link Budgets

In an acoustical communication system, transmission loss is caused by energy spreading and sound absorption. Energy spreading loss depends only on the propagation distance, but the absorption loss increases with range and frequency. Just like other links, these problems set the limit on the available bandwidth. Link condition is largely influenced by the spatial varying condition of the underwater acoustic channel. Acting like a waveguide, the seabed and the air/water interface. Various phenomena, including formation of the shadow zones, evolve from this variation. Transmission loss at a particular location can be predicted by many of the propagation modeling techniques with various degrees of accuracy. Spatial dependence of transmission loss imposes severe problems for mobile communication systems with both the transmitter and receiver moving.

Ambient noise, together with frequency dependent transmission loss, determines the relationship between the available range-bandwidth and SNR at the receiver input.

Distance	Bandwidth
1000 km	< 1 kHz
10-100 km	~2-5 kHz
1-10 Km	10 kHz
< 100 m	100 kHz

Table 6.1 Amount of Bandwidth available in an acoustical link with respect to link distance[8]

6.3 Underwater Optical Link Budget

Many factors must be considered when calculating a “true” link budget; Weather, wavelength of the laser, distance of the link, underwater currents, scattering, misalignment, attenuation, absorption, and data rates are just a few of the things that must be considered. Other factors such as the light source (laser, LED), detector (PIN, APD), and other bottleneck electronics must also be considered.

6.4 Geometric Effects in Link Budget

In the underwater environment especially in turbid water scattering can be expected to be the dominate effect. In addition to attenuating the signal, the scattering can also be viewed as strongly influencing the transverse intensity of the beam profile. This can also result in very stringent pointing requirements since the percentage of forward scattered light will be strongly peaked at small angles.

6.5 Building an Underwater Link Model

The main motivation as the topic for this thesis was to research the possibility of using semiconductor light sources as a mean to communicate underwater. However, as described above, scattering and the variable optical qualities of ocean water need to be considered. These varying properties change with time and location which in turn could affect the amount of light lost.

6.6 Link Budget Results

The results of these graphs are consistent with our intuition that with worsening water conditions a shift from blue ~450 nm to green wavelengths ~ 550 nm is appropriate. Also the performance tends to be higher for a laser based system. However, for type I water it is likely that the range of the laser may be slightly overestimated due to not included effects. In all cases it also looks like the performance of an LED based solution may be sufficient for short 42 ranges. Other issues such as the field of view and dynamic range of the receiver will be important.

The following graphs illustrate this by considering several different water types with different light sources. It was assumed that a detector capable of detecting signals at the -50 dB level is available; using this one can estimate the expected range for different wavelengths.

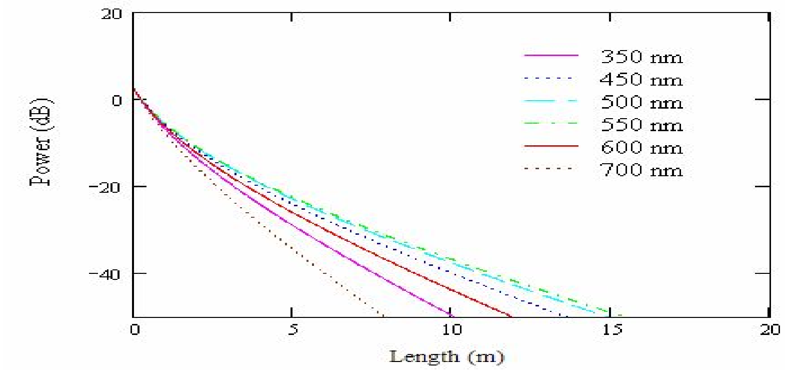

Figure 6.1:1 W LED, in Type II water with particulate, CDOM, chlorophyll, and scattering

7. Figure of Merits for Underwater Platform

At first, the figure of merit for comparing communications systems would appear to be energy per bit and bit-rate length product. One can either consider the attempted throughput of data or the good throughput of data, or the Bit Error Rate as inputs. It is simplest to assume the goodput of data through the system, considered as the product of bitrate and range. The amount of additional encoding to ensure the goodput of data can be factored in after the initial computation. In many scenarios, for example the transmission of real-time video, dropping of data bits is not crucial. However practical underwater communication systems are constrained in size, weight, and power. There are also additional operational constraints such as minimum speeds at which the platform can maintain neutral buoyancy and heading especially in the presence of a current. This can be an important issue when pointing stability between the transmitter and receiver is required. The problem with this approach is that decisions have to be made about the relative weighting of different factors. This has been a problem for example in considering how to compare power systems for underwater vehicles. One can construct a system for example that has a very high power density which may seem good, but may end up not being able to reach the desired speed thus defeating the purpose.

8. High Powered LEDS

Recently, high powered LEDs have been commercialized for applications requiring high efficiency including automobile head lights, brake lighting, and indoor lamp lighting.

As a possible future application the possibility of using high powered LEDs for underwater communications were explored where the desired wavelengths of operation are between 450nm and 550nm. As described in chapter 3 these wavelength have the least attenuation in ocean water. For optical communication purposes the following aspects should be considered:

- Optical wavelength
- Optical output power
- Reliability
- Beam parameters.

LumiLEDs are presently the industry leader in high powered LEDs. They have focused on efficiently extracting light from the LEDs and packaging the LEDs so that heat can efficiently be removed. They have three LED wavelengths that could be considered for underwater applications, Blue, Cyan, and Green. The spectrum for each color LED can beseen in the graph below.

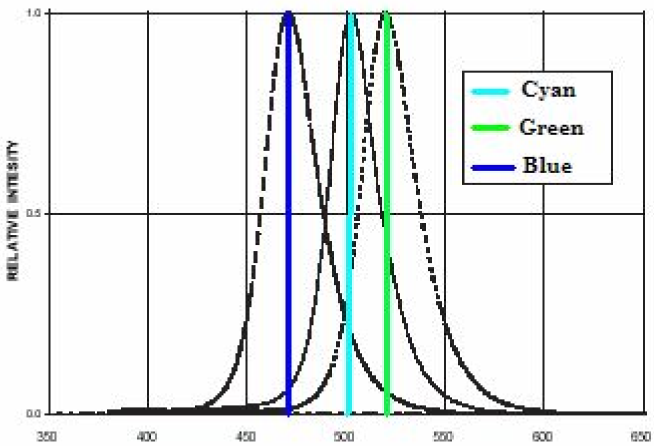

Figure 8.1: Output wavelength from Superflux LED's: Blue, Green, and Cyan[2].

Output power is the next consideration. Typical 5mm high brightness LED's with
similar wavelengths were purchased from Digikey's online parts catalog and were compared to LumiLED's Superflux. The results from this comparison can be seen in the below table.

Color/Wavelength (nm)	High Brightness LED from Digikey (Min in mcd)	LumiLED's Superflux LED (Min in mcd)
Blue / 475	120	900
Cyan / 505	400	2700
Green / 525	400	2700

Table 8.1: Comparison between Typical 5mm high brightness LED's and LumiLED's Superflux[1,2].

The Superflux LED's are superior in output power with the desired wavelength operation. Next the reliability must be considered. A normal LED's brightness can be increased with an increased drive current. The extra flux will be exchanged for decreased reliability and lifetime. The Superflux

LEDs, with their almost 650% advantage in light intensity, still maintain their reliability. This has been a major focus of the LumiLED's research and is summarized below.

Stress Condition	**Failure Rate**
Temp = 55 C, I = 70 mA	<0.027
Temp = 85 C, I = 45 mA	<0.30
Temp = -40 C, I = 70 mA	<0.06

Table 8.2 Reliability testing of Lumiled's Superflux LED's from Ref[2]

In many LED applications the characteristics of the output beam are not that important; however in an optical communications system the ability to collimate a beam is very important. In a conventional packaged LED the semiconductor material is seated in a reflective cup with two terminal leads which is all incased in a transparent epoxy. One of the leads is located at the base with the other wirebonded to the top of the die.

Figure 8.2: Conventional packaged LED, Right) LumiLED's package

8.1 Superflux LED

In the case of GaN LEDs on sapphire substrates there are two top contacts since the sapphire is insulating. The combination of the reflective cup, plastic epoxy, and lead overhang in a conventional LED, leads to a distorted light image. This causes and increases the difficulty of forming a collimated beam. The Superflux LEDs have a similar setup as a typical LED, but LumiLED has optimized the design such that the image is not distorted, in addition to taking special care forming a good lens with the epoxy.

Figure 8.3 Image of die in conventional packaging, Right) Image of die in LumiLed Packaging.

LumiLED also has a 1W LED available called the Luxeon Star/O that is designed to optimize the optical efficiency for white lighting applications. Incorporated in the package are reflective and refractive optical elements to evenly distribute the light. In order to dissipate the heat generated from the junction, LumiLED attached a meal plate in the back to act has a heat sink. This heat sink allows the LED to run at full load and still stay cool to the touch. The Star/O was purchased to be tested in the 10 Mb communication link, unfortunately this LED could not sustain its optical output at the circuit's 10 MHz modulation speeds. The bandwidth of the LED was limited to about 1MHz due to the very large size of the LED die.

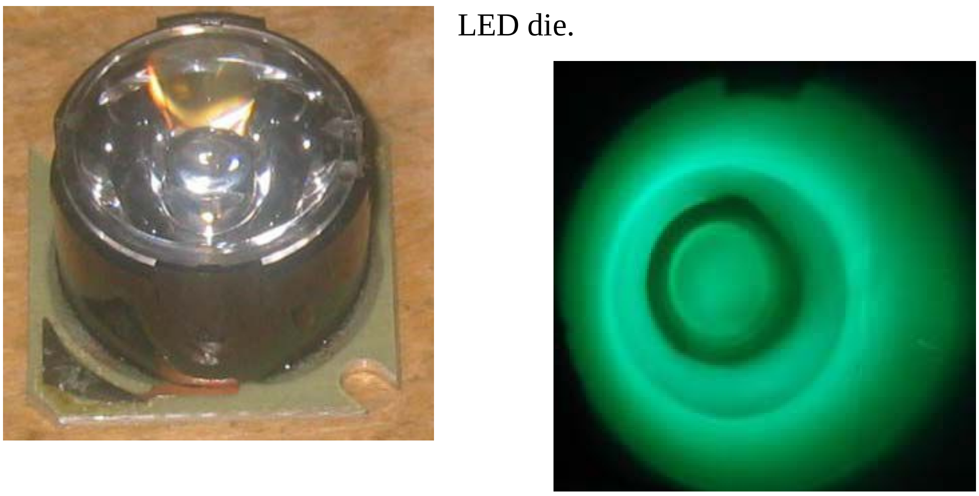

Figure 8.4 :Luxon Star/O package, Right) Luxeon Star/O die image.

Overall LumiLEDs were found to be suitable for use in free space optics, although the bandwidth could be substantially increased if the die were patterned such that many small small LEDs with small capacitance could be driven simultaneously.

9. FM Optical Wireless System

The next experiment demonstrated the use of LEDs in a simple communication link using human voice. FM modulation was chosen over AM modulation since it was viewed as being more resistant to fading and variations in the signal amplitude. There were two versions of the Circuit built. The first version used the 4ns pulser circuit, seen below This worked fine even though the duty cycle of the pulses was extremely short (4ns at 100kHz). This was accomplished by using a Schmitt Trigger to recognize when a pulse was received and convert the signal into a 50% duty cycle square-wave. To produce a system

with lower overall power requirements as second generation was also constructed that uses a logic chip as the LED driver. In this circuit the Schmitt Trigger was not necessary since the duty cycle of ~50% was created by the LED driver. The populated board of the second generation chip is shown in Figure Below.

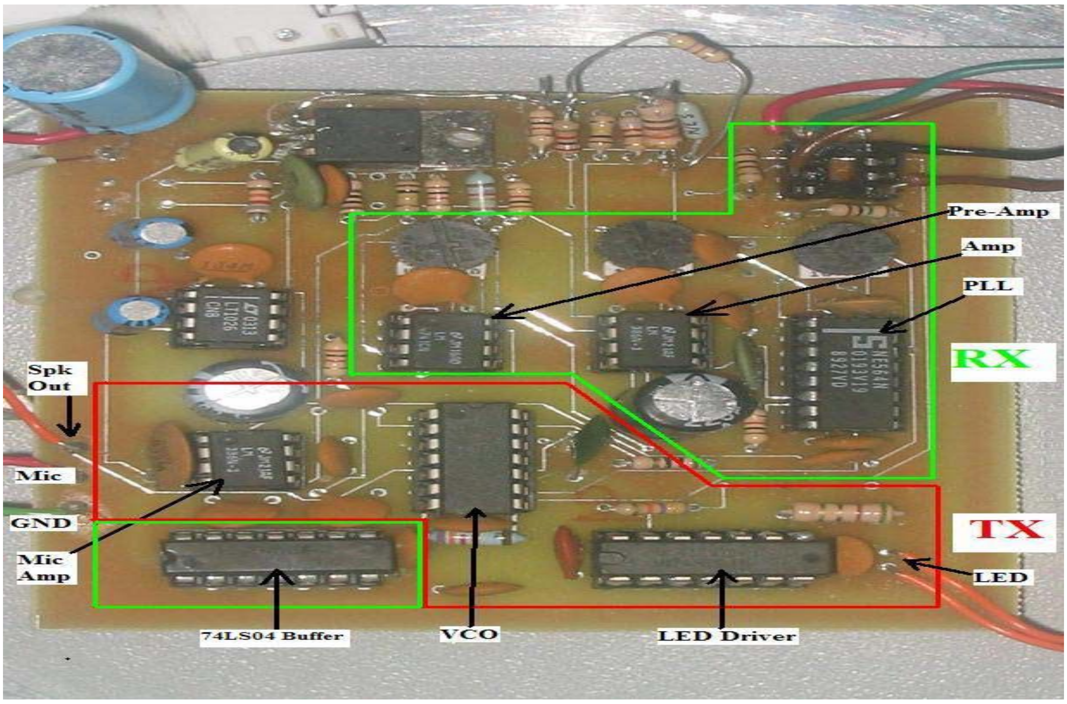

Figure 9.1: Circuit Diagram of FM 2-way voice LED link

The output of the circuit was not a 4 ns pulse but it had a nice 3.5 volt square-wave output with a 50% duty cycle. The NE564 phase-locked loop had an easier time locking on to a 50% which deleted some of the pulse cleaning circuitry on the front end of the receiver. A block diagram of the second generation board can be seen below.

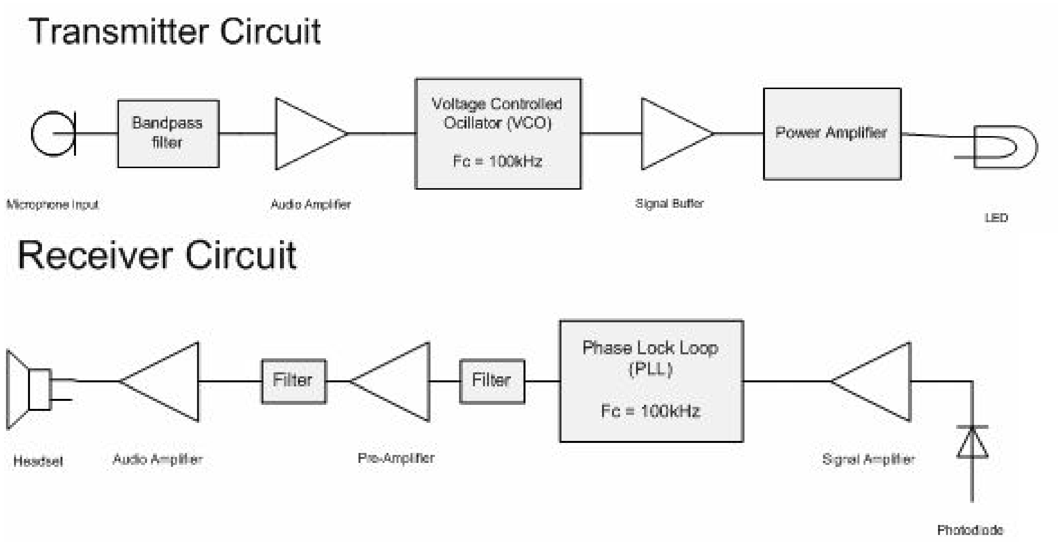

Figure 9.2 Circuit block diagram of FM optical wireless system

10.Transmitter

.10.1Microphone

The microphone circuit consisted of the microphone and resistors and capacitor network. The resistors that are chosen are crucial for its proper functionality. If the value is too large, the audio amplifier will become saturated and clip the incoming audio signal. If the value is too small, the microphone will not be sensitive enough to use at a reasonable distance.

10.2 Band-pass Filter & Audio Amplifier

The voice is then sent through a band-pass filter. The band-pass filter is 1st order filter using passive components set for the voice frequency (VF). Even though the human voice is capable of sounds between 100Hz to 10 kHz, capacitors and resistors were chosen to pass signal from 300Hz to 5kHz since these are the main useful frequencies. Filtering the 66 signal also reduces background and white noise. The filtered signal was then amplified with a LM386 audio amplifier with 10X gain. This gave a 1 to 2 volt signals for reasonable sound pressure levels on the microphone.

10.3 Voltage Controlled Oscillator

A Voltage Controlled Oscillator is an oscillator that changes its frequency according to a control voltage feed to its control input. An ICL8038 precision waveform generator/voltage controlled oscillator was used to generate the frequency modulated output to the LED pulser circuit. It was difficult to find a voltage to frequency converter in the 100 kHz range and this synthesizer chip provided a relatively simple solution. An additional advantage of this chip is that it has small temperature coefficients resulting is a stable frequency. The output of the oscillator is a 50% duty cycle square-wave set to a center frequency of 100 kHz. The frequency was set by two external resistors and one external capacitor. Load impedances have to be taken into account due to the sensitivity of the IC. If the load resistance was to change due to temperature, pressure, or if circuit sees a voltage drop due to battery drain, then the VCO has the potential to change center frequencies. This was observed experimentally when the load of the LED pulser circuit changed very slightly, roughly 2-4 ohms due to the battery supply being drained, one could see a swing in frequencey of plus and minus 10-20 kHz.

It was observed that when the external frequency setting resistor and capacitor shifted due temperature fluctuation, the center frequency would shift. The receiving circuit would have a hard time demodulating the shifted signal, thus causing signal degradation. The use of a crystal oscillator instead of the set resistor and capacitor could potential solve this issue.

10.4 Signal Buffer, Power Amplifier, & LED

The final stages of the transmitter are the signal buffer and power amplifier. A 74LS04 inverter was used as a signal buffer. Placing the buffer between the VCO and the power amplifier greatly reduced the noise on the receiver side when no input signal from the microphone was present. As a lower power alternative to the pulser circuit a LED driver consisting of three stacked 74HS04 inverters was constructed by placing the outputs in parallel.

11. Receiver

11.1 Photo detector & Built-in Amplifier

The first part of the receiver is the photo detector and built-in amplifier. For the collection of light an 8-pin DIP OPT210 monolithic photodiode and amplifier were used. The integrated combination of photodiode and transimpedence amplifier on a single chip reduce the problems commonly encountered with discrete designs such as leakage current errors, noise pick-up, and gain peaking due to stray capacitance. This chip is no longer being produced, but was able to be obtained from a surplus chip vender. This chip also limited the

frequency of operations since the bandwidth was 300 kHz. However this disadvantage was more than offset by the ease of use of the chip which only required 4 connections to function.

11.2 Phase-Locked Loop FM Demodulator

The next stage a NE564 phase-locked loop was used to demodulate the 100 kHz modulated received signal. An external capacitor and potentiometer in parallel are connected to the set pins for the internal voltage controlled oscillator. The potentiometer allows for fine adjustments to the locking frequency. The output from the internal VCO is connected to the internal phase comparator. The PLL then compares in incoming frequency to the internally running frequency. When the center frequency is the same as the free running frequency it is considered “Locked” and the clean demodulated signal is outputted to the pre-amplifier. For the PLL to “Lock” the pulse has to be a certain shape and duty cycle. If the received pulse is a square-wave with a 50% duty cycle, then the PLL

will lock. If the received pulse becomes distorted into a sharp pulse or triangle shape, the PLL will have a difficult time locking which will cause distortions in the demodulated signal.

11.3 Filter & Pre-amplifier

The demodulated signal is now a low frequency analog signal that requires amplification. The output of the NE594 PLL chip is less than 10mV. A preamplifier is used to increase the signal to an acceptable level. It is possible to use just one amplifier, LM386 audio amplifier, but the signal would be distorted and could potential low a speaker. The lower the gain multiply the better the sound quality. High end car amplifier companies use dozens of amplifiers to get the sound quality they desire. As a pre-amp a LM741 was used with a max gain of 10X. To reduce the amount of noise that is amplified through the chip, filtering capacitors were connected at the input stage before amplification occurred. This greatly improved sound quality and clarity.

11.4 Filter, Audio-amplifier, & Speaker

The use of a basic LM386 audio amplifier and some more filtering capacitors are used to amplify the analog signal one more time. The audio amp is setup for an 8 ohm load at a max of 10X gain. To maximize efficiency an 8 ohm speaker is connected from the output to ground. Using a matched load maximized the efficiency of the circuit and allow for better sound delivery to the end user. For user friendliness, a 10Kohm potentiometer was used to control the output gain.

12. Conclusion/Summary

The future tactical ocean environment will be increasingly complicated. In addition to traditional communication links there will be a proliferation of unmanned vehicles in space, in the air, on the surface, and underwater. To effectively utilize these systems improvements in underwater communication systems are needed. Since radio wave do not propagate in sea water, and acoustic communication systems are relatively low bandwidth the possibility of high speed underwater optical communication systems are considered.

Applications for underwater optical communication systems include:

- Diver-to-diver communication links

- Diver-to-submarine links
- Submarine-to-UAV links
- Submarine-to-submarine links
- UAV-to-UAV links
- Submarine-to-satellite links

In this thesis there were two principle components a theoretical modeling effort of underwater link budgets and an experimental effort to build LED based systems suitable for underwater communications.

The model describing the inherent optical properties of ocean water, included:

- Absorption by Pure Seawater
- Absorption by Chlorophyll
- Absorption by Color Dissolved Organic Matter
- Scattering by Pure Seawater
- Scattering by Small & Large Particle
- Beam Spread through a horizontal water column

Chlorophyll is a major cause of loss in optical beam power. It is also very hard to find and exact quantity of chlorophyll since it changes with location, time of day, season, and depth in 82 the water column. The assumption was made that the chlorophyll was distributed homogeneously throughout the water column. Then, a theoretical link budget was constructed and estimates for 3 underwater scenarios were found. These 3 scenarios were and there corresponding link estimate are listed below:

- A blue/green LED based, bottom moored buoy system operating in relatively shallow water. 1W LED - **estimated link distance ~16 m**
- A blue/green laser based system operating in deep clear ocean water with unlimited power and size constraints. **10W Laser - estimated link distance ~425 m**
- A power and size constrained, diode laser system suitable for small unmanned underwater vehicle operation. **1W Laser - estimated link distance ~75 m**

In the clearest of ocean conditions a link of ~425 m could be possible. Underwater optical wireless links could be used in many applications with this distance. However, this estimate is limited by not including scintillation caused by: temperature fluctuation, current and wind, dispersion, and beam steering.

Acoustical communications will still stand as the primary source of underwater communications, but the research has shown optics may have a place in the underwater environment. These products will take time and more research to develop, but the thesis research presented has taken the first few steps in making underwater optical communications a reality.

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