The International Journal Of Engineering And Science (IJES)
|| Volume || 4 || Issue || 5 || Pages || PP.61-68 || 2015 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Design of Underwater wireless optical/acoustic link for reduction of back-scattering of transmitted light

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ABSTRACT
Underwater communication plays a significant role in the study of climate change through ocean monitoring and associated sensor networks. It is severely limited when compared to free space communication because water is essentially opaque to electromagnetic radiation except in the visible band. Even in the visible band, light penetrates only a few hundred meters in the clearest waters and much less in turbid waters due to the presence of suspended sediment or high concentrations of marine life. Consequently, acoustic techniques are been used for underwater communication systems which is relatively mature and robust. Acoustic systems are capable of long range communication. But traditional underwater acoustic communications cannot provide high enough data rates to enable monitoring technology. Optical wireless communications, centred around blue-green wavelengths, are being used as an alternative. Here a hybrid design is being introduced using an optical/acoustic link to reduce back scattering of transmitted light.
Keywords – *Absorption coefficient, Acoustic transmission loss, Extinction, Extinction coefficient, Optical attenuation*

Date of Submission: 13-May-2015 Date of Accepted: 25-May-2015

I. INTRODUCTION

High speed, robust communication is unavoidable in modern science, but is still very much a technical limit in underwater applications. In air, RF Communications operate over long distances at high data rates while using modest power. This is not feasible in water due to the high absorption of electromagnetic signals at radio frequencies. Optical fibers are used for high data rate links in fixed undersea applications, such as telecommunication cables, but are too expensive for use in most science applications, and are not appropriate for mobile assets. The energy required for optical data transmission is much less than acoustics when considered on a bits per Joule basis, which translates into modest battery usage for large data transfers [1]. Underwater optical duplex communications are hindered by the large amount of back-scattered light caused by the ocean. This is because back-scattered light can be indistinguishable from the light of the return signal. The purpose of this work is to develop a novel, duplex underwater link design which can be used for ocean monitoring which utilises the strong aspects of both acoustic and optical communications & the main application is communication between a buoy or ships, with unmanned and autonomous underwater vehicles (UUV and AUV respectively) and divers.

II. UNDERWATER COMMUNICATION

2.1 NOISE IN THE OCEAN

Noise in the ocean is frequency dependent. There are three major contributors to noise underwater:

- ambient noise which represents the noise in the far field;
- self noise of the vehicle (considered out of band noise);
- intermittent noise sources including noises from biological sources such as snapping shrimp, ice cracking and rain.

A significant challenge for data transmission underwater is multipath fading. The effect of multipath fading depends on channel geometry and the presence of various objects in the propagation channel. Multipath's occur due to reflections (predominately in shallow water), refractions and acoustic ducting (deep water channels), which create a number of additional propagation paths, and depending on their relative strengths and delay values can impact on the error rates at the receiver. The bit error is generated as a result of inter symbol interference (ISI) caused by these multipath signals.

2.2 OPTICAL WIRELESS COMMUNICATION

Optical wireless communications (OWC) is a form of optical communication in which unguided visible, infrared (IR), or ultraviolet (UV) light is used to carry a signal.

OWC systems operating in the visible band (390–750 nm) are commonly referred to as visible light communication (VLC). VLC systems take advantage of light emitting diodes (LEDs) which can be pulsed at very high speeds without noticeable effect on the lighting output and human eye. VLC can be possibly used in a wide range of applications including wireless local area networks, wireless personal area networks and vehicular networks among others. On the other hand, terrestrial point-to-point OWC systems, also known as the free space optical (FSO) systems, operate at the near IR frequencies (750–1600 nm). These systems typically use laser transmitters and offer a cost-effective protocol-transparent link with high data rates, i.e., 10 Gbit/s per wavelength, and provide a potential solution for the backhaul bottleneck. There has also been a growing interest on ultraviolet communication (UVC) as a result of recent progress in solid state optical sources/detectors operating within solar-blind UV spectrum (200–280 nm). In this so-called deep UV band, solar radiation is negligible at the ground level and this makes possible the design of photon-counting detectors with wide field-of-view receivers that increase the received energy with little additional background noise. Such designs are particularly useful for outdoor non-line-of-sight configurations to support low power short-range UVC such as in wireless sensor and ad-hoc networks.

Based on the transmission range, OWC can be studied in five categories:

- Ultra-short range OWC: chip-to-chip communications in stacked and closely packed multi-chip package
- Short range OWC: wireless body area network (WBAN) and wireless personal area network (WPAN) applications under standard IEEE 802.15.7, underwater communication
- Medium range OWC: indoor IR and visible light communications (VLC) for wireless local area networks (WLANs) and inter-vehicular and vehicle-to-infrastructure communications.
- Long range OWC: inter-building connections, also called Free-Space Optical Communication (FSO).
- Ultra-long range OWC: inter-satellite links.

2.3 UNDERWATER OPTICAL COMMUNICATION

In recent years, underwater wireless optical communications (UWOC) has attracted considerable attention as an alternative technology to traditional acoustic approach. As a special type of free space optical (FSO) communications, UWOC systems employ the blue/green region of visible light spectrum to realize data transmission since this region of light suffers lowest attenuation in natural water. Due to these advantages, UWOC has numerous applications such as real-time video communications, remote sensing and navigation, imaging as well as high throughput sensor network. The absorption and scattering may introduce the effects of energy loss and direction changing for the optical beams, respectively. In turbid medium especially coastal and harbour water, the transmitted photons are scattered multiple times, which is referred to as multiple scattering.

High speed underwater optical communications has at least three distinct advantages over acoustic communications. The data rates achievable are high (1 to 10Mbps), the latency from when data is sent to when data is received is low, and there is no acoustic noise associated with transmission. High data rates are advantageous in data retrieval applications, where, for one example, wireless data retrieval would make deployment and recovery of certain systems more economical. [2]

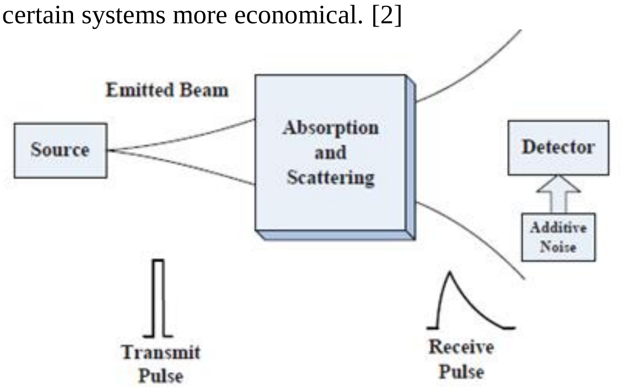

Fig 1: system model of underwater optical communication link

Light pulses propagating in aquatic medium suffer from attenuation and broadening in the spatial, angular, temporal and polarization domains. The attenuation and broadening are wavelength dependent and result from absorption and multi-scattering of light by water molecules and by marine hydrosols (mineral and organic matter). Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) have been in service since the 1950s to perform underwater tasks, such as collecting data and retrieving items. Operation of these vehicles are challenging, but oil resources are found further offshore, ROV's and AUV's are required to go deeper and stay deployed for a longer time to perform critical tasks. One such task is to monitor a deep sea oil well. Sending tethered ROV's thousands of meters below the surface in order to conduct survey is expensive and time consuming. To overcome this challenge, we need an underwater optical wireless communication system. [3] Unlike radio frequencies, the technology requires no spectrum licenses, which makes it easy to be deployed widely. Besides, it has attractive characteristics of dense spatial reuse and low power usage per transmitted bit.

The amount of visible light reflected varies according to the angle of incidence of the visible light. The amount of light that actually enters the sea depends on the angle of the sun, sea surface conditions, sky conditions and clarity of sea water. As light travels through sea water, it loses its intensity due to absorption and scattering which can be classified as absorption of light by sea water, absorption of light by suspended particles, scattering of light by sea water and scattering of light by suspended particles. Common term for both these losses is called extinction. Extinction is sum of loss of light intensity due to absorption and loss of light intensity due to scattering.

2.4 EXTINCTION COEFFICIENT

Rate of decrease in light intensity can be expressed as a means of a coefficient called extinction coefficient. It is actually a measure of reduction of solar light intensity on a vertical distance.
Extinction coefficient is high for sea water because of mainly three factors

- Minute suspended particles in ocean water scatters light strongly.
- Dissolved yellow substance is present in sea water
- Abundance of plankton

Due to the presence of minute suspended particles, ocean water scatters light strongly. These suspended particles also absorb radiation. In addition, the dissolved yellow substance present in sea water is responsible for greater absorption of light radiation. As a result of all these, the extinction coefficient of sea water is greater than that of pure water. In the higher latitude regions of the oceans, waters are normally less transparent due to the abundance of plankton in them. So extinction coefficients in the sea water are more in these waters. Extinction coefficient is greater in south-west monsoon season due to the increase in suspended sediment load as well as the increase in plankton biomass in the waters. In the winter season, extinction coefficient is somewhat less due to decrease in sediment load. Also extinction coefficient is generally high in the morning hours and then decreased slowly reaching minimum at noon time. There after, the values increased till evening. Since extinction coefficient is a measure of reduction of solar light intensity on a vertical distance, at low sun during morning and evening, the extinction coefficients increased since the vertical distance to which the rays penetrate will be less. On the other hand, when the sun is directly overhead at noon time, extinction coefficient decreased as the vertical distance to which the sun rays penetrate will be more.

III. HYBRID LINK

The downlink of the duplex communication system, from the ship or base station to the AUVs, is a wide-angle low-bandwidth acoustic link which is also used for tracking and locating the AUVs. Meanwhile, the multiple uplinks are high-bandwidth, highly directional optical links. [4]

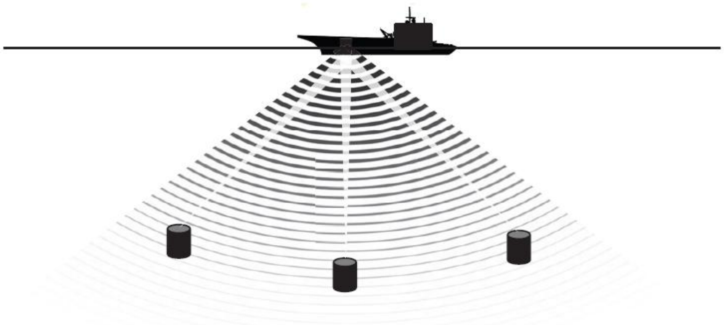

Fig 2: Hybrid communication link environment

The purpose of the underwater AUVs is to relay high volumes of monitored data to the base station where it processes the information. The AUVs are coordinated through transmission of configuration, location and movement information.

3.1 OPTICAL (UPLINK) TRANSMISSION

The UUC collects information from the underwater system. This information is modulated, amplified and transmitted to the receiver which then detects this optical signal using a photo detector. This is then amplified using an optical amplifier and demodulated to obtain the electrical output. This electrical output is processed to obtain the information.

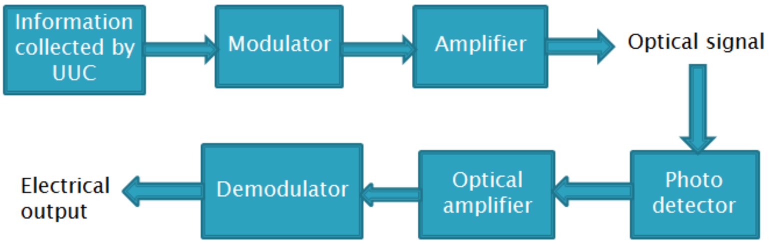

Fig 3: Block diagram of uplink transmission

3.2 ACOUSTIC (DOWNLINK) TRANSMISSION

A simple diagram of the data transmission scheme involving a projector (transmitter) and a hydrophone (receiver) is as shown in figure. A hydrophone is a microphone designed to be used underwater for recording or listening to underwater sound. Most hydrophones are based on a piezoelectric transducer that generates electricity when subjected to a pressure change. Such piezoelectric materials, or transducers can convert a sound signal into an electrical signal since sound is a pressure wave

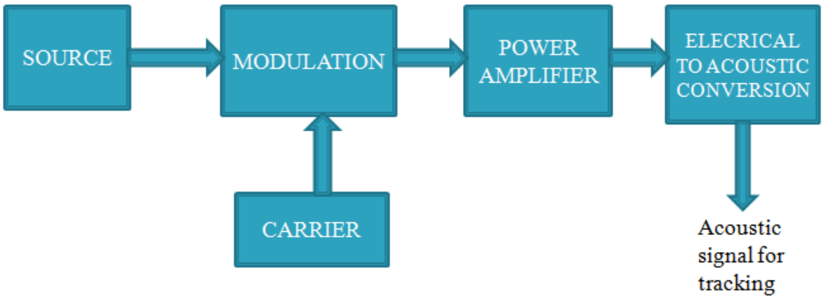

Fig 4: Block diagram of acoustic transmitter

The transmitter takes the collected sensor and navigational data and formats it into packets at the Data Source and this is then modulated with the carrier frequency. The modulated signal is amplified to a level sufficient for signal reception at the receiver. There is an optimum amplification level as there is a trade-off between error free transmission and conservation of battery energy. The acoustic power radiated from the transmitter is proportional to the electrical power supplied to it.

On the receiver side, the sensitivity of the hydrophone converts the sound pressure that hits the hydrophone to electrical energy, calculated in dB/V. Signal detection, includes amplification and shaping of the input to determine a discernible signal. Here a detection threshold needs to be reached and is evaluated as the ratio of the mean signal power to mean noise power (SNR). The carrier frequency is then supplied for demodulation, before the transmitted data is available for use within the vehicle for either data storage or for input into the vehicles control and navigation requirements.

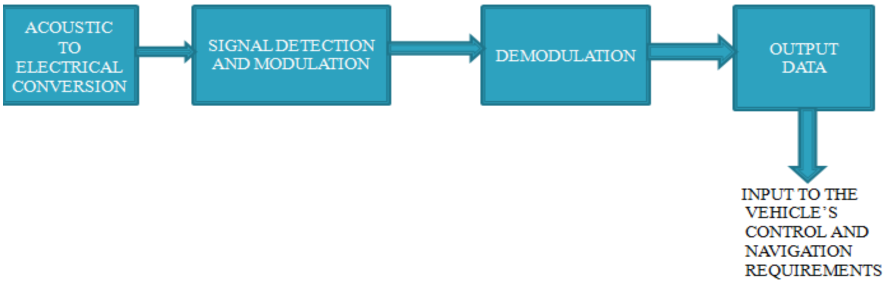

Fig 5: Block diagram of acoustic receiver

IV. INDENTATIONS AND EQUATIONS

4.1 EXTINCTION COEFFICIENT

The extinction co-efficient c(\λ) of the aquatic medium is governed by the absorption and scattering coefficient α(λ) and β(λ) respectively

$$C(\lambda) = \alpha(\lambda) + \beta(\lambda)$$

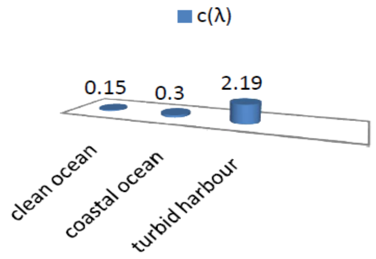

Fig 6: Ocean division based on extinction coefficient

4.2 OPTICAL ATTENUATION

Optical attenuation is caused by scatter and absorption of transmitted photons. These losses are characterized by the attenuation coefficient c, which is dependent on the source wavelength. Fractional optical transmission losses O are described as [5]

$$O(z,\lambda) = e^{-c(\lambda)z}$$

λ is the transmission wavelength which is 445 nm. In addition to wavelength dependence, attenuation is influenced by optical properties of the transmission medium, which for the ocean is a direct consequence of the composition. This can lead to the attenuation coefficient varying by up to an order of magnitude from 0.1 m^{-1} in clear open ocean to 2.19 m^{-1} in turbid regions.

The optical SNR is found from the transmission loss through [5]

$$SNR(z,\lambda) = \left(\frac{P_T O(z,\lambda) D^2 cos\phi}{(\tan^2\theta) 4z^2 N_O}\right)^2$$

Where P_T is the transmitter power, D is the receiver aperture diameter, ϕ is the offset angle between the center of the transmitter and receiver, θ is the transmitter fov and N_O is the noise equivalent power.
Here λ=445 nm, c=0.15m^{-1}, P_T=100mW, D=0.01m2, ϕ=0˚, N_O=9.9x10^{-22}W.

4.3 LARGE SCALE PATH LOSS IN UNDERWATER ACOUSTIC NETWORK

The growing need for ocean observation and remote sensing has recently motivated a surge in research publications as well as several experimental efforts in the area of underwater acoustic networks. Crucial to these developments is the understanding of propagation conditions that define the time-varying and location-sensitive acoustic environment, not only from the viewpoint of small-scale, rapid signal fluctuations that affect the performance of the physical layer techniques, but also from the viewpoint of large-scale, slow fluctuations of the received signal power that affect the performance of higher network layers. One of the challenges in the design of underwater acoustic networks is the allocation of power across different network nodes. This task is exacerbated by the spatial and temporal variation of the large-scale transmission loss, and the lack of statistical models that capture these apparently random phenomena. [6]

Total path loss in an acoustic channel, for a link *z* metres long at frequency *f*, is given by [7]

$$A(z,f) = A_0 z^k a(f)^z$$

Where A_0 is a unit normalizing constant which includes fixed losses, a(f) is the absorption coefficient, caused primarily by viscosity, and k is the spreading factor, typically quoted as 1.5.

Extensive measurements of absorption losses over the last half century has lead to several empirical formulae which take into account frequency, salinity, temperature, pH, depth and speed of sound. The absorption coefficient, which is frequency dependent, can be estimated using Thorp's empirical equation (valid when f>5Khz) [7]

$$10\log a(f) = \left(\frac{0.11f^2}{1+f^2}\right) + \left(\frac{44f^2}{4100+f^2}\right) + \left(\frac{2.75f^2}{10^4}\right) + 0.003$$

Where f is measured in kHz and the attenuation constant in dB/km. It is valid for frequencies from 100Hz to 1MHz and is based on seawater with salinity of 35% ppt, pH of 8, temperature of 4°C and depth of 0 m (atmospheric pressure) which is assumed but not stated by Thorp. In Thorp's model, the attenuation is independent of temperature and the depth of the water body.

The acoustic transmission loss is used to calculate the SNR, where S_z is the power spectral density of the transmitted signal and N is the noise figure [8]

$$SNR(z,f) = \frac{S_z(f)}{A(z,f)N(f)}$$

This relation means it is possible, with acoustic systems, to communicate beyond 1000 kilometres [9], as long as the transmission bandwidth is low and initial power high; medium length links of 100-1000 metres support up to 20 – 50 kHz [9]. Underwater acoustic communication channels are characterized by a path loss that depends not only on the distance between the transmitter and receiver, as it is the case in many other wireless Channels, but also on the signal frequency. The signal frequency determines the absorption loss which occurs because of the transfer of acoustic energy into heat[10].

V. EXPERIMENTS & RESULTS

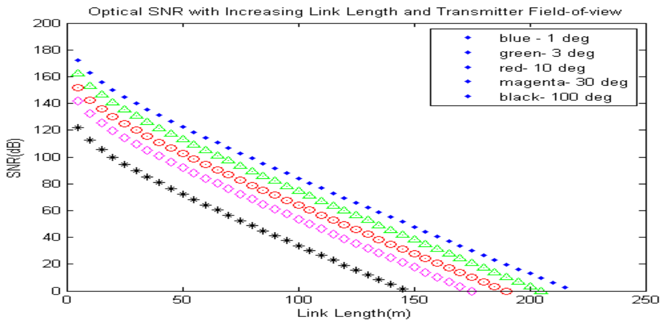

Fig 7: Optical SNR with increasing link length and transmitter field of view for clean ocean for hybrid link

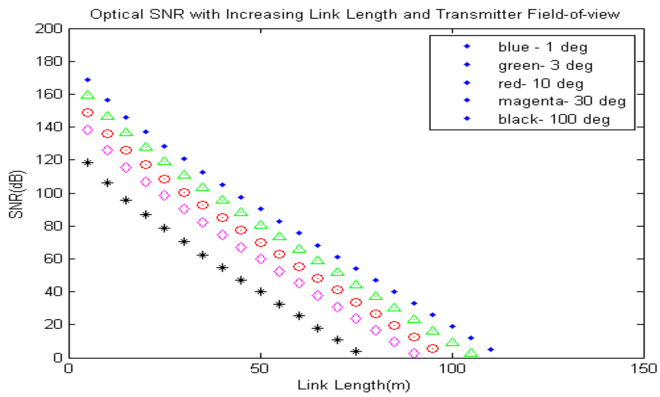

Fig 8: Optical SNR with increasing link length and transmitter field of view for coastal ocean for hybrid link

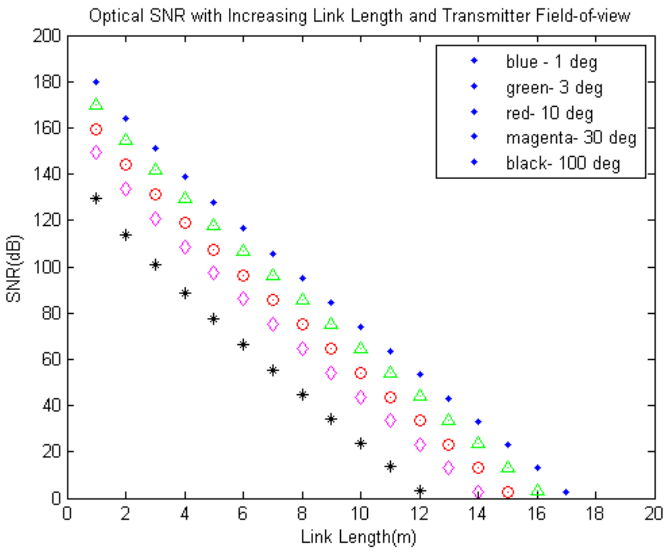

Fig 9: Optical SNR with increasing link length and transmitter field of view for turbid harbor for hybrid link

TRANSMITTER FIELD OF VIEW	MAXIMUM RANGE (m)		
	CLEAN OCEAN	COASTAL OCEAN	TURBID HARBOUR
1°	245	130	19
3°	240	120	18
10°	225	115	17
30°	200	105	16
100°	175	90	14

TABLE: Comparison between three different ocean scenarios

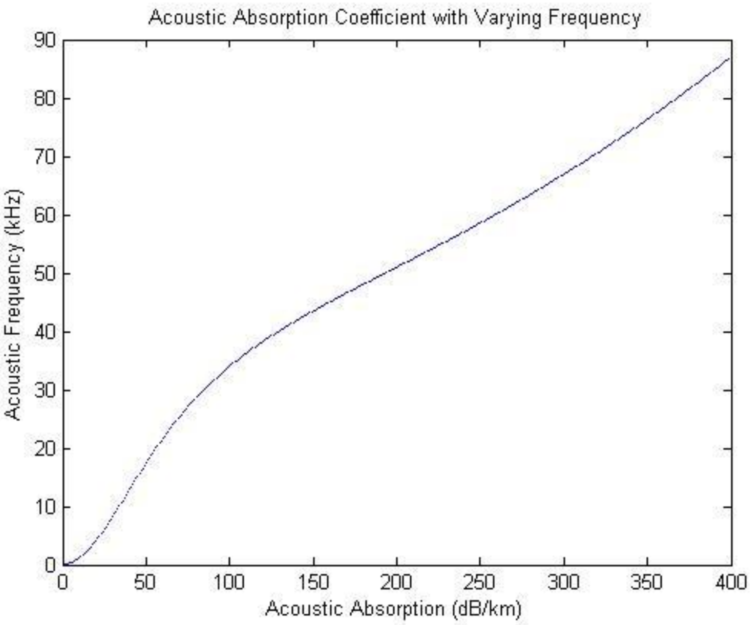

Fig 10: Acoustic absorption coefficient with varying frequency

VI. SUMMARY OF RESULTS

The figures 7,8 and 9 illustrates optical signal to noise ratio with increasing link length and transmitter field of view for a clean ocean, coastal ocean and turbid harbour scenarios respectively.. The blue pattern indicates minimum transmitter field of view(fov) and hence has maximum SNR and also maximum transmission range when compared to the other transmitter fov's. This is being plotted after considering a noise of $9.9x10^{-22}$ W. It is clear that since the coastal ocean waters contain more dissolved salts and plankton, it has a larger extinction coefficient decreasing the transmission range when compared to clean ocean scenario. Turbid harbour is having the maximum extinction coefficient of 2.19. Hence the rate of decrease of light intensity in vertical direction will be higher when compared to the clean and coastal ocean scenarios. It can be seen from the graph that the transmission range is minimum for this case as the losses due to absorption and scattering is maximum in this case.

VII. CONCLUSION

The figures shows how rapidly the signal quality degrades as FOV and distance increases; a 100m 1° link has the same SNR performance as a 40m link with a 100° FOV in the case of clean ocean. As a consequence, longer distance underwater communication are highly directional. The advantage of using an acoustic downlink is that instructional information and tracking can be transmitted to the AUV's regardless of whether they are beyond the optical transmission range or not. Tracking also allows for narrow FOV lasers to be used as corrective locational information can be sent to the AUVs. Acoustic attenuation increases significantly with frequency, where doubling the bandwidth from 30 to 60 kHz causes the acoustic absorption to roughly double.

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