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# A Comparative Study of Underwater Wireless Optical Communication for Three Different Communication Links

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***Abstract**: The importance of underwater wireless optical communication has grown recently for applications of underwater observation and sea monitoring systems. This communication technology is expected to play a prominent role in investigating climate changes, prediction of natural disasters, and discovery of natural resources, marine biology in lake, sea and ocean environments. Acoustic technology is mostly used for establishing wireless communication link among divers and ships, or sending long range remote signals. Sound waves travel through water faster than in air, receiving very little attenuation. Due to frequency attenuation characteristic of acoustic waves in water, it is difficult to expand its bandwidth. Acoustic approach cannot achieve high data rate, and also portable communication devices are difficult to be designed at lower cost. So the best option is to go for an underwater optical wireless communication system.*
***Keywords:** Acoustic communication, Extinction Coefficient, LOS, Modulating Retro Reflecting link, Reflective link,*

## I. Introduction

As scientific progress demands more and varied data from the earth's oceans, and the military requires greater scrutiny of undersea traffic and threats, the need for reliable underwater communication links increases. The mobility requirements of submarines and autonomous underwater vehicles make tethered links Infeasible, and radio frequency electromagnetic waves are highly attenuated in ocean water, preventing their widespread use. [1]. As sound waves undergo very little attenuation in the underwater channel, underwater acoustic communications has been a topic of research for some time [2,3]. However, due to issues of multipath interference and lack of bandwidth, acoustic data rates are limited [4]. Acoustic links also exhibit very long propagation delays. Underwater communication is of great interest to military, industry, and scientific communities. Underwater vehicles, sensors, and observatories require a communications interface with data rates in the few to tens of Mbps. While fiber optic or copper cabling can be used for sufficiently large or stationary devices, a wireless link is desirable in many situations. [5]

## II. Underwater Acoustic Communication

The signals that are used to carry digital information through an underwater channel are not radio signals, as electro-magnetic waves propagate only over extremely short distances. Instead, acoustic waves are used, which can propagate over long distances. However, an underwater acoustic channel presents a communication system designer with many difficulties. [6]

Major challenges in the design of underwater acoustic networks are: [7]
- The available bandwidth is severely limited;
- The underwater channel is severely impaired, especially due to multi-path and fading;
- Propagation delay in underwater is five orders of magnitude higher than in radio frequency (RF) terrestrial channels, and extremely variable;
- High bit error rates and temporary losses of connectivity (shadow zones) can be experienced, due to the extreme characteristics of the underwater channel;
- Battery power is limited and usually batteries cannot be recharged, also because solar energy cannot be exploited;
- Underwater sensors are prone to failures because of fouling and corrosion.

## III. Underwater Optical Communication

Free-space optical communication (FSO) is an optical communication technology that uses light propagating in free space to wirelessly transmit data for telecommunications or computer networking. Free space means air, outer space, vacuum, or something similar. The technology is useful where the physical connections are impractical due to high costs or other considerations. The advantages of FSO are Ease of deployment , Can be used to power devices, License-free long-range operation (in contrast with radio communication) , High bit rates, Low bit error rates, Immunity to electromagnetic interference and Full duplex operation. Underwater free-space optical communication has witnessed a surge in interest from developments in blue-green sources and detectors [8],[9],[10],[11]. These take advantage of the “blue-green optical window” of relatively low attenuation of blue-green wavelengths of the electromagnetic spectrum underwater. Attenuation underwater is due to intrinsic absorption by water, dissolved impurities, organic matter, scattering from the water, and impurities including organic and inorganic particulates. Hence, different types of water will have different degrees of attenuation. [12]

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. [13] 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.

### 3.1 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.

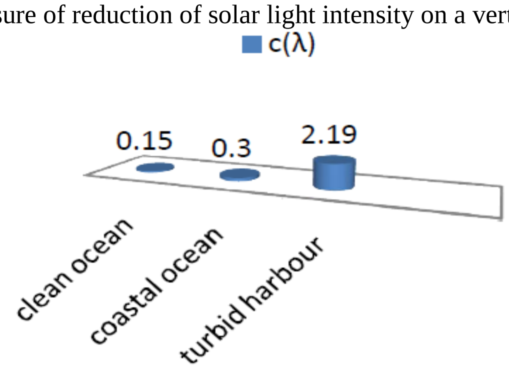


**Fig :** Ocean division based on extinction coefficient

The extinction co-efficient c(\λ) of the aquatic medium is governed by the absorption and scattering coefficient $\alpha(\lambda)$ and $\beta(\lambda)$ respectively

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

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.
The propagation loss factor as a function of wavelength and distance z is given by

$$Lpr(\lambda, z) = \exp(-c(\lambda)z)$$

## IV. Communication Link Models

We now consider three types of communication links: the line of sight, the modulating retro reflector, and the reflective.

### 4.1 Line-of-Sight Communication Link

Line of sight is a straight and unobstructed path of communication between transmitter and receiver. Thisis the most common link between two points in optical wireless communication system. In this scenario, the transmitter directs the light beam in the direction of the receiver.

The optical signal reaching the receiver for a line of sight communication link is obtained by multiplying the transmitter power, telescope gain, and losses and is given by

$$P_{R\_LOS} = P_T \eta_T \eta_R L_{pr}\left(\lambda, \frac{d}{\cos\theta}\right)\left(\frac{A_{Rec}\cos(\theta)}{2\pi d^2\,(1-\cos(\theta_0))}\right)$$

Where $P_T$ is average transmitted optical power, $\eta_T$ is the optical efficiency of transmitter, $\eta_R$ is optical efficiency of receiver, d is perpendicular distance between transmitter and receiver, θ is angle between the perpendicular to the receiver plane and the transmitter-receiver trajectory, $\theta_0$ is laser beam divergence angle and $A_{Rec}$ is receiver aperture area.

### 4.2 Modulating Retro Reflector Communication Link

A retroreflector is a device or surface that reflects light back to its source with a minimum amount of scattering. The angle of incidence at which the device or surface reflects light in this way is greater than zero, unlike a planar mirror. The coefficient of luminous intensity is the measure of reflector performance which is defined as the ratio of the strength of the reflected light or luminous intensity to the amount of light that falls on the reflector which is the normal illuminance. A reflector will appear brighter as the coefficient value increases. Coefficient of luminous intensity is a function of the colour, size and condition of the reflector. Clear or white reflectors are the most efficient and appear brighter than other colours. The surface area of the reflector is proportional to the coefficient of luminous intensity and increases as the reflective surface increases.
The brightness of a reflector is also a function of the distance between the light source and the reflector. At a given observation angle, as the distance between the light source and the reflector decreases, light that falls on the reflector increases. This increases the amount of light returned to the observer and the reflector appeared brighter. A Modulating Retro Reflector (MRR) system combines an optical retro reflector and an optical modulator to reflect modulated optical signals directly back to an optical receiver or transceiver, allowing the MRR to function as an optical communication device without emitting its own optical power. This can allow the MRR to communicate optically over long distances without needing substantial on-board power supplies. In operation, the interrogator illuminates the retro-reflecting end of the link with a continuous wave beam. The retro reflector actively reflects this beam back to the interrogator while modulating the information on it.
The optical signal reaching the receiver for a modulating retro reflective link is given by

$$P_{R_{Retro}} = P_T \eta_T \eta_{Retro}\, \eta_{Rec}\, L_{pr}\left(\lambda, \frac{2d}{\cos\theta}\right)\left[\frac{A_{Retro}\cos\theta}{2\Pi d^2(1-\cos\theta_0)}\right]\left[\frac{A_{Rec}\cos\theta}{\Pi(d\tan\theta_{0Retro})^2}\right]$$

Where $\eta_{Retro}$ is the optical efficiency of the retroreflector, θ is the angle between the perpendicular to the receiver plane and the transmitter-receiver trajectory, $A_{retro}$ is the retro reflector's aperture area, $\theta_{Retro}$ is the retro reflector's beam divergence angle.

**4.3 Reflective Link**

In some communication scenarios the line of sight is not available due to obstructions, misalignment, or random orientation of the transceivers. To address this problem a reflective communication link could be used. In this case, the laser transmitter emits a cone of light, in the upward direction. The light reaching the ocean-air surface illuminates an annular area and is partially bounced back in accordance with the reflectivity. Since the refractive index of air is lower than that of water, total internal reflection (TIR) can be achieved above a critical incidence angle.

For a reflective link, Equation describes annular area taken from a sphere of radius h+x, $\theta_{min}$ and $\theta_{max}$ are the inner and outer angles of the laser cone.

$$A_{ann} = 2\pi\,(h+x)^2(1-cos(\theta_{max})-1+cos(\theta_{min}) = 2\pi(h+x)^2(cos(\theta_{min})-cos(\theta_{max})$$

The optical signal reaching the receiver for reflective link is given by

$$f_{Ref} = \frac{P_T\,cos(\theta)}{(A_{ann})} = \eta_T\eta_R L_{pr}\left(\lambda,\frac{h+x}{cos(\theta)}\right)\left(\frac{1}{2}\right)\left\{\left(\frac{tan(\theta-\theta_t)}{tan(\theta+\theta_t}\right)^2 + \left(\frac{sin(\theta-\theta_t)}{sin(\theta+\theta_t}\right)^2\right\} \qquad for \quad \theta_{min} \le \theta \le \theta_c$$

$$f_{Ref} = \eta_T\eta_R L_{pr}\left(\lambda,\frac{h+x}{cos(\theta)}\right), \qquad \text{for} \quad \theta_c \le \theta \le \theta_{max}$$

**Table I. Parameters Used For Numerical Calculation**

| Parameter | Value |
|---|---|
| Extinction coefficient for<br>• Clean ocean<br>• Coastal ocean<br>• Turbid harbour | <br>0.15<br>0.30<br>2.19 |
| Critical angle(deg) | 48.44 |
| Optical efficiency for<br>• Retro reflector<br>• Transmitter<br>• Receiver | <br>0.9<br>0.9<br>0.9 |
| Transmitter power(W) | 1 |
| Receiver aperture area ($m^2$) | 0.01 |
| Retro reflector aperture area ($m^2$) | 0.01 |
| Retro reflector beam divergence ($\theta_{retro}$)(deg) | 10 |
| Beam divergence angle $\theta_0$ (deg) | 68 |
| Transmitter inclination angles $\theta_{min}$, $\theta_{max}$ | 0,68 |
| Transmitter depth h(m) | 20 |
| Receiver depth x (m) | 20 |

## V. Figures & Tables

**6.1 Line Of Sight Communication Link**

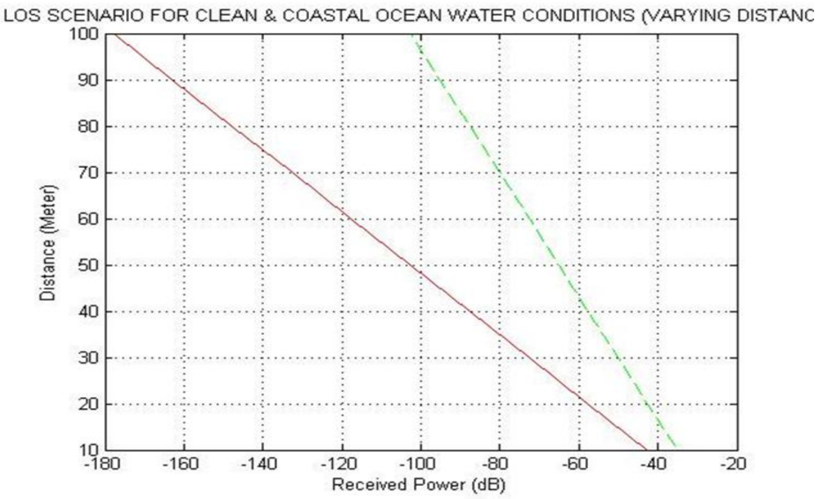


**Fig 1:** LOS scenario for clean (green) and coastal ocean (red) water conditions (for varying distance)

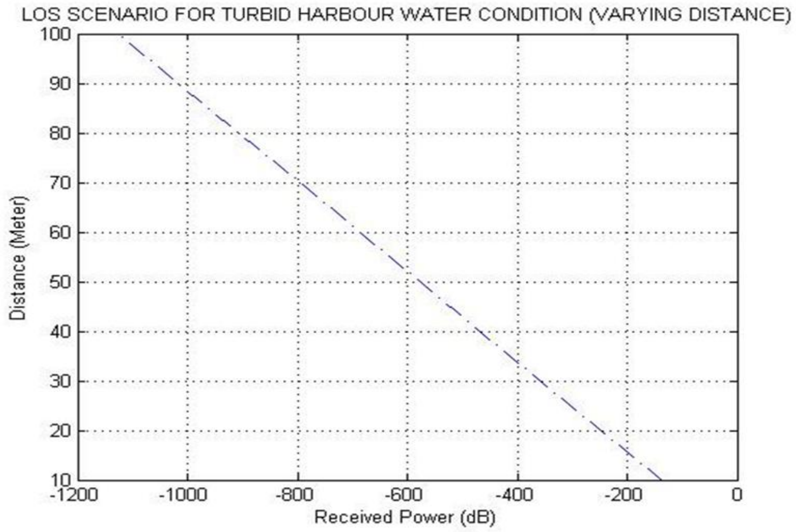


**Fig 2** LOS scenario for turbid harbour water condition (for varying distance)

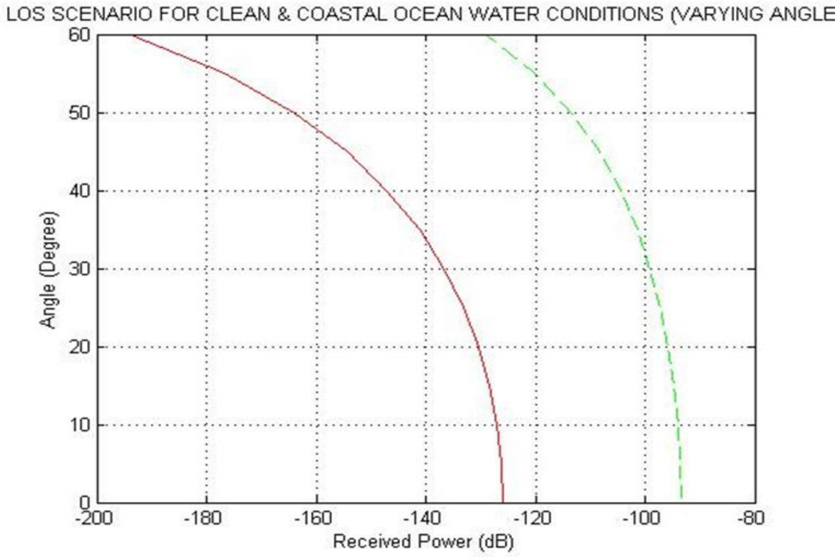


**Fig 3:** LOS scenario for clean (green) and coastal (red) ocean water condition (varying angle)

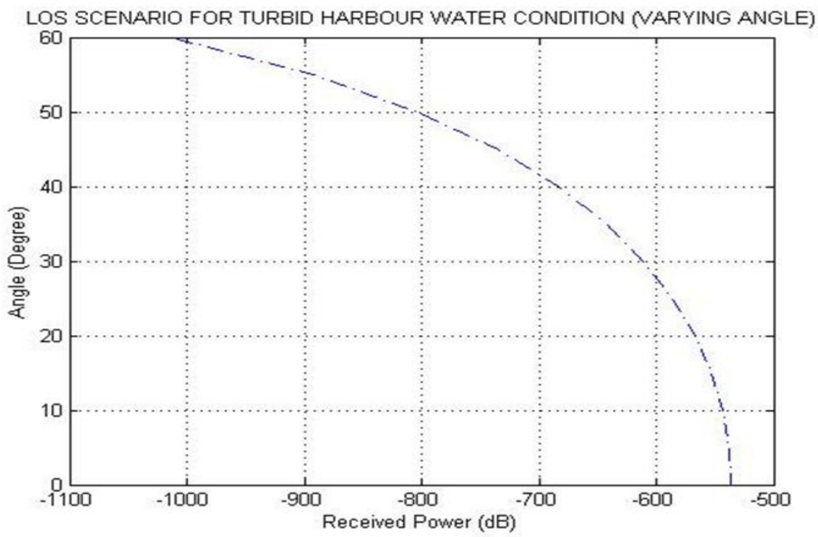


**Fig 4:** LOS scenario for turbid harbor water condition (varying angle**)**

**6.2 Modulating Retro Reflective Link**

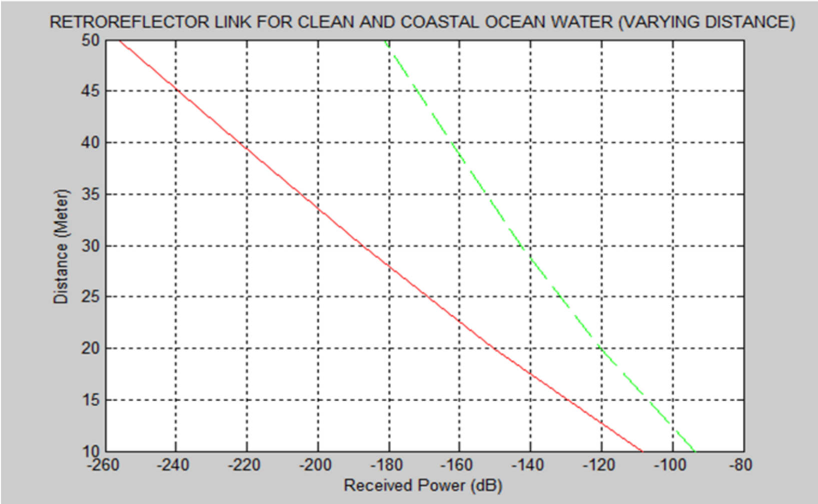


**Fig 5:** Retro reflective link scenario for clean (green) and coastal ocean (red) (varying distance)

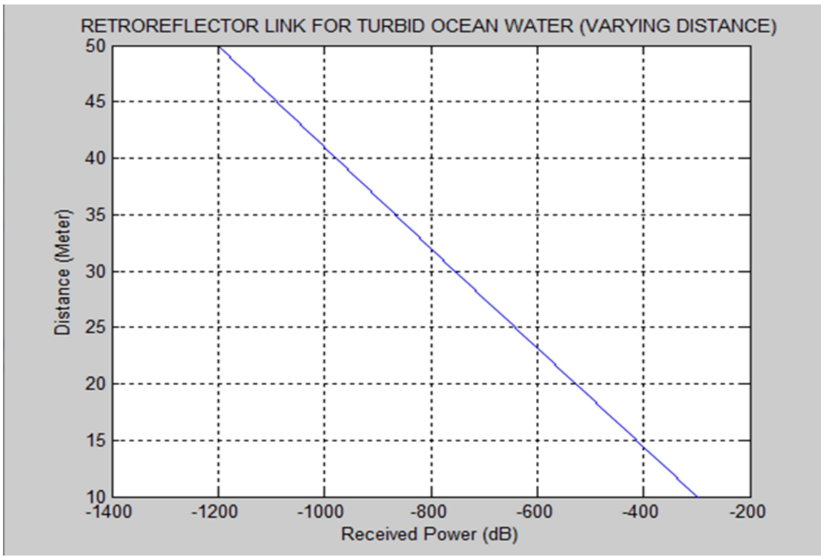


**Fig 6:** Retro reflective link scenario for turbid ocean (varying distance)

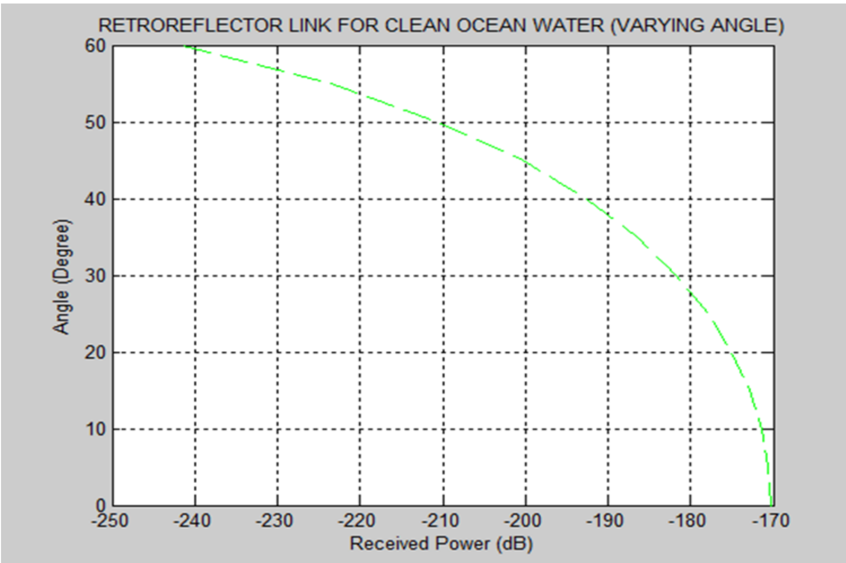


**Fig 7:** Retro reflective link scenario for clean ocean (varying angle)

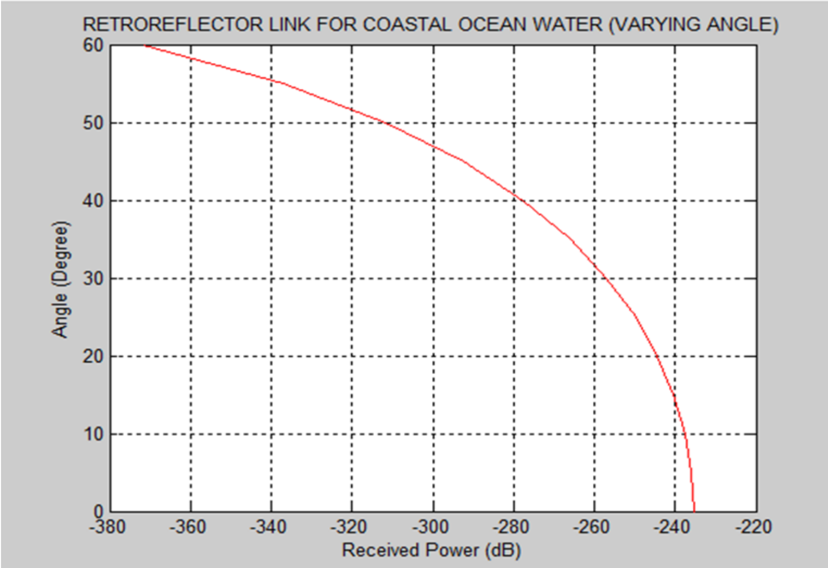


**Fig 8:** Retro reflective link scenario for coastal ocean (varying angle)

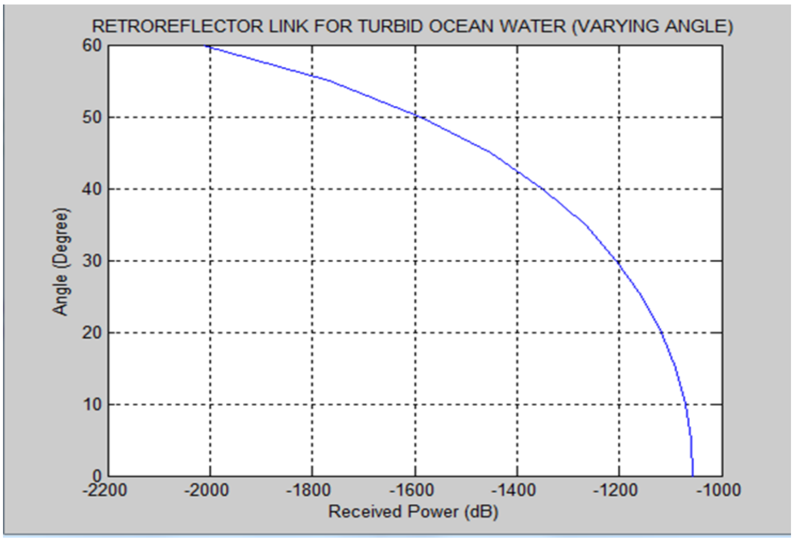


**Fig 9:** Retro reflective link scenario for turbid ocean (varying angle)

**6.3 Reflective Link**

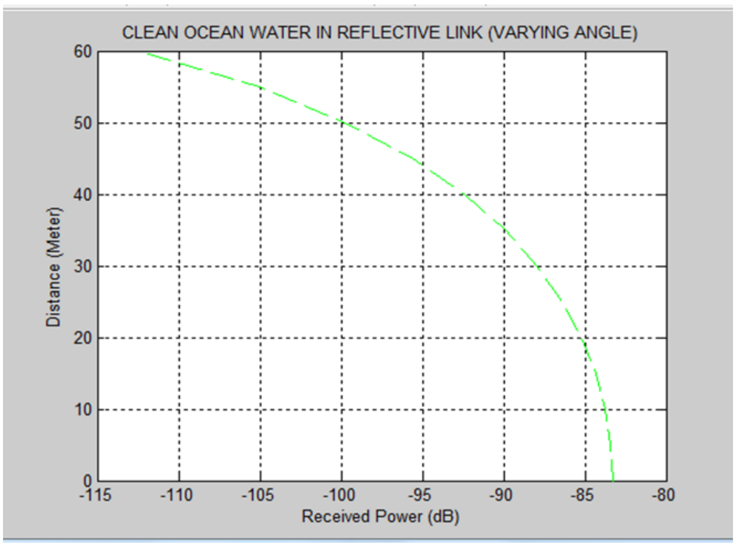


**Fig 10:** Reflective link scenario for clean ocean

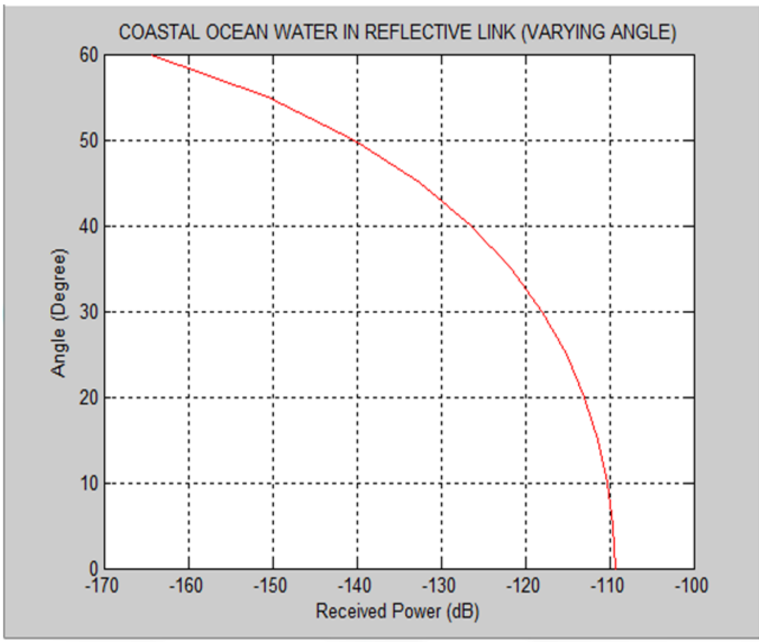


**Fig 11:** Reflective link scenario for coastal ocean.

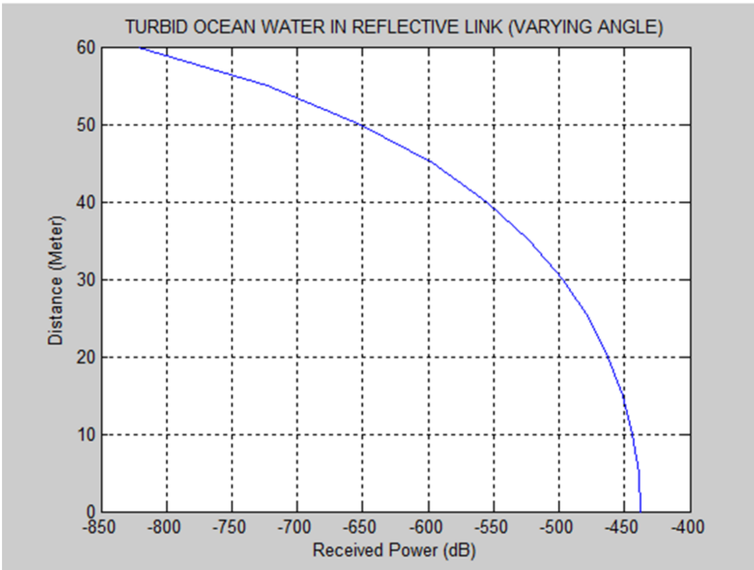


**Fig 12:** Reflective link scenario for turbid ocean

The received power versus distance is plotted for the three communications links ie Line of sight, Modulating retro reflective link and reflective link. The received power is tabulated (TABLE II) for two different values of θ where θ is the angle between the perpendicular to the receiver plane and the transmitter-receiver trajectory.

**Table II: Received Power For Three Links For Varying Angle**

| TYPE OF LINK | CLEAN OCEAN | | COASTAL OCEAN | | TURBID OCEAN | |
|---|---|---|---|---|---|---|
| | θ=0˚ | θ=60˚ | θ=0˚ | θ=60˚ | θ=0˚ | θ=60˚ |
| LOS | -93.41 | -128.99 | -125.98 | -194.13 | -536.39 | -1015.32 |
| REFLECTIVE LINK | -83.27 | -112.34 | -109.33 | -164.46 | -437.66 | -821.11 |
| RETRO REFLECTIVE LINK | -170.32 | -241.49 | -235.47 | -371.78 | -1056.3 | -2013.4 |

**Table III: Received Power For Los And Retro Reflective Link With Varying Distance**

| TYPE OF OCEAN | LOS LINK | | RETRO REFLECTIVE LINK | |
|---|---|---|---|---|
| | D=10m | D=100m | D=10m | D=50m |
| CLEAN OCEAN | -35.08 | -102.66 | -93.46 | -181.35 |
| COASTAL OCEAN | -42.51 | -177.83 | -108.44 | -256.26 |
| TURBID HARBOUR | -137.24 | -177.83 | -297.23 | -1200.23 |

The received power versus the perpendicular distance between transmitter and receiver is being compiled and tabulated (TABLE III) for line of sight link and modulating retro reflective link. This factor doesn't come into effect for the reflective link scenario as denoted in the formulae. As the turbidity of the water increases (i.e. extinction coefficient) the absorption of light also increases and hence the losses at the receiver end also increases. Thus Maximum efficient communication can be performed in the clean ocean scenario with minimum loss. Communication in turbid harbour waters causes reduction in the data rate and results in an ineffective communication. Power received in the retro reflective link is less than that in the reflective link.

## VI. Conclusion

A comparative study of underwater wireless optical communication for three different communication links wad done. Line of sight communication link, Modulating Retro reflector link and Reflective link was the three links used for the analysis. The received power in all the three cases was compared for three different parts of the ocean namely clean ocean, coastal ocean and turbid harbor. Results showed that since the turbid harbor had the maximum extinction coefficient of 2.19, the received power value was the least for turbid ocean in all the three communication links studied. Maximum power was noted for clean ocean under all the three scenarios because of least reduction of solar energy in the vertical direction. $\theta$ is angle between the perpendicular to the receiver plane and the transmitter-receiver trajectory. As $\theta$ value increased, the received power was found to decrease. Received power also decreased as the perpendicular distance between the transmitter and receiver increased.

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