Underwater Neutrino Communication – Issues and Solutions

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Abstract—Unlike above-water communications developments, which have brought us instantaneous cell phone conversations, wireless internet and myriad other advances, underwater communications lags behind. There are wide ranges of physical processes that impact underwater communications and the relative importance of these processes are different in different environments. In this paper we have shown an alternative way to communicate underwater using a sub-atomic particle known as Neutrino. It also describes some issues with neutrino communication and some suggestions are given. Its high penetration properties, half integer spin, neutrino oscillation has enhanced the possibilities for deep sea communications. Oscillation probabilities, neutrino detection, Cherenkov radiation, pulse position modulation (PPM) are all briefly discussed.

Keywords— Underwater Robotics, Underwater Communications, Neutrino Flavor Oscillations, Cherenkov Radiation, Photomultiplier, Neutrino Flux, Muon Decays.

I. INTRODUCTION

Oceans cover about 70 percent of the Earth’s surface, and much of this vast resource remains unexplored. Existing means of underwater communication are electromagnetic signals, optical fiber networks, acoustic signal propagation. There is a need to improve the wireless communication capacity of underwater robots. Main focus is to find better ways of transmitting communication signals to improve capacity to the point where underwater robots no longer have to be chained by a heavy, expensive communications cable, but can instead transmit their readings to other robots, or to shipboard researchers.

The high rate of absorption of electro-magnetic signals in sea water has limited the development of electromagnetic communications systems to a few specialized systems. Using Electromagnetic Waves doesn’t work well in sea water due to the conducting nature of the medium [11]. Similarly, optical signals are also rapidly absorbed in sea water and have the added disadvantage of scattering by suspended particles and high levels of ambient light in the upper part of the water column. These optical waves are limited to very short distances because the severe water absorption at the optical frequency band. Acoustic waves in water can be adversely affected by temperature gradients, surface ambient noise and multipath propagation due to reflection and refraction.

Apart from these naïve approaches another way to communicate in deep sea between robots is through Neutrinos [15]. The basic concept of Neutrino communication derived from the fact that can traverse the entire planet with a very little loss of intensity. Unfortunately, due to the fact of weak interactions of Neutrino with matter makes it undetectable on present Neutrino detectors. Neutrinos need to have minimum threshold energy of 1.8MeV to be detected. So far there’s no detection method for low energy Neutrinos.

A high intensity Neutrino can be generated by feeding high energy proton beam into a target made of liquid mercury which will produce pion particles, which in turn will decay into muons, which in turn decay into muon neutrinos. These neutrinos then can be sent from transmitter located in one underwater robot to the receiver of another robot. Neutrinos are electrically neutral so cannot be deflected by any electromagnetic interference. Current designs for such a facility assume $10^{14}$ s$^{-1}$ useful muon and $10^{14}$ s$^{-1}$ useful antimuon decays with muon energies in the range from 25-50 GeV. Such a facility also would constitute the first step towards a multi-TeV muon collider. The short life-time of the muon and the high proton beam power are the main technical challenges [5], [12].

II. RELATED WORK

There has been numerous works on the trial on detection of Neutrinos on large scale. Super-Kamiokande is a neutrino observatory which is under Mount Kamioka near the city of Hida, Gifu Prefecture, Japan. The observatory was designed to search for proton, study solar and atmospheric neutrinos and keep watch for supernovas in the Milky Way Galaxy [4], [8], [9], [14].

The Super-K is located 1,000 m (3,300 ft) underground in the Mozumi Mine in Hida’s Kamioka area. It consists of a cylindrical stainless steel tank that is 41.4 m (136 ft) tall and 39.3 m (129 ft) in diameter holding 50,000 tons of ultra-pure water. The tank volume is divided by a stainless steel superstructure into an inner detector (ID) region that is 33.8 m (111 ft) in diameter and 36.2 m (119 ft) in height and outer detector (OD) which consists of the remaining tank volume.
Mounted on the superstructure are 11,146 photomultiplier tubes (PMT) 20 in (51 cm) in diameter that face the ID and 1885 8 in (20 cm) PMTs that face the OD. There is a Tyvek and blacksheet barrier attached to the superstructure that optically separates the ID and OD.

The Sudbury Neutrino Observatory (SNO) is a neutrino observatory located 6,800 feet (about 2 km) underground in Vale Inco’s Creighton Mine in Sudbury, Ontario, Canada. The detector was designed to detect solar neutrinos through their interactions with a large tank of heavy water. The detector turned on in May 1999, and was turned off on 28 November 2006. While new data is no longer being taken the SNO collaboration will continue to analyze the data taken during that period for the next several years. The underground laboratory has been enlarged and continues to operate other experiments at SNOLAB.

MINOS (or Main Injector Neutrino Oscillation Search) is a particle physics experiment designed to study the phenomena of neutrino oscillations, first discovered by a Super-Kamiokande (Super-K) experiment in 1998. Neutrinos produced by the NuMI (“Neutrinos at Main Injector”) beamline at Fermilab near Chicago are observed at two detectors, one very close to where the beam is produced (the near detector), and another much larger detector 735 km away in northern Minnesota (the far detector).

### III. UNDERWATER NEUTRINO COMMUNICATION

#### A. NEUTRINO EMISSION

Muon storage rings have been proposed as source of highly collimated neutrino beams in order to allow precision measurements of the neutrino mixing parameters. In these facilities muons will be produced from pion decay and the pions are produced by proton irradiation of a target. Current designs for such a facility assume $10^{14}$ s$^{-1}$ useful muon and $10^{14}$ s$^{-1}$ useful anti-muon decays with muon energies in the range from 25-50 GeV. Such a facility also would constitute the first step towards a multi-TeV muon collider. The short life-time of the muon and the high proton beam power are the main technical challenges [5], [7], [12].

The muon neutrino flux from a storage ring with unpolarized muons of energy $E_o$ is given by:

$$\frac{d\Phi}{dE_\nu} = \frac{2E_oN_\mu}{m_\mu^6\pi L^2} \left(1 - \beta\right) E_\nu^2 \left[3m_\mu^2 - 4E_o E_\nu (1 - \beta)\right]$$  (1)

Where $N_\mu$ is the number of muon decays,

$$\beta = \sqrt{1 - \frac{E_\mu^2}{E_o^2}}$$  (2)

Where $m_\mu$ denotes the muon mass and L is the Cartesian distance from the storage ring. The beam divergence, $\theta_o=m_\mu/E_o$. These neutrinos will interact in sea water and produce muons in this process, with a cross section of

$$d\sigma/dE_\mu = \sigma_0 \left(Q + \bar{Q} E_\mu/E_\nu^2\right)$$  (4)

With $\sigma_0 = 1.583 \times 10^{-42}$ m$^2$, $Q = 0.41$ and $\bar{Q} = 0.08$. The cross section for anti-neutrinos is obtained by interchanging $Q$ and $\bar{Q}$. The range of a muon, $R$, with energy $E_\mu$ in water can be parameterized as $R = 14.5m + 3.4E_\mu$ GeV$^{-1}$ m in range $E_\mu = 20-150$ GeV. The resulting muon flux $\phi_\mu$ per unit area is obtained from

$$\phi_\mu = \frac{10^6 \rho N_A}{2} \int_0^{E_\nu} dE_\nu \int_{E_o}^{E_\nu} dE_\mu \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_\mu} R$$  (5)

Where $\rho = 1.02$ g cm$^{-3}$ is the density of sea water, $N_A=6.3 \times 10^{23}$ is Avogadro’s number and $E_o$ is the smallest acceptable muon energy. The anti-muon flux is obtained by replacing the cross section and flux with the corresponding quantities for anti-neutrinos. The requirement that the muon direction is within less than a maximum angle $\theta_o$, of the original neutrino direction, translates, by simple kinematics, into a lower bound $E_o$ on the muon energy $E_\mu$, $E_o = E_\mu/(1 + 2E_\nu/\theta_o^2)$. Also, we may set a minimum muon energy $E_{min}$, every muon should have, in which case $E_o = max \{E_o, E_{min}\}$. From (2) we obtain including both neutrinos and anti-neutrinos, with $\theta_o = 10^\circ$, $E_{min} = 10^4 GeV$, $E_o = 150 GeV$, $N_\mu = 10^4 s^{-1}$, $L = 10^6 km$ and $A_o = 10^3 m^2$, which is the area in which a muon can be detected, a muon rate of $\phi_\mu = 2.2 s^{-1}$; note that

$$\phi_\mu \propto E_o^4$$  (6)

A neutrino source delivering muons at a rate of $10^{14}$ s$^{-1}$ with energy of 150 GeV would require about 4MW in proton beam power and 2.4MW acceleration power, which for a 10% electrical efficiency translates into a total power consumption of roughly 65MW. In order to aim the beam, it is necessary to point the long straight section of the muon storage ring towards the robot. The storage ring is relatively large, but also quite lightweight and thus one solution could be to suspend the storage ring in water, either in a lake or close to shore, and use buoyant forces to aim it but stronger magnets combined with shorter straight sections, can reduce the size of the ring substantially.

#### B. NEUTRINO DETECTION

Neutrinos can be detected by two known methods:

1) Generating beams of neutrinos by accelerating muons to high energy, which then decay, producing Neutrinos that are tightly collimated. Detecting Neutrinos is simply this process in reverse. When the Neutrinos interact with matter, they produce muons that can be detected easily [15]. The most straightforward approach to muon detection is to convert the chassis itself into a muon detector. We would use thin muon detector modules which can be used very much like wallpaper to cover the majority of the vessel’s hull. The muons would enter on one side of the chassis and leave it on the other side. The entry and exit points are measured and thus the muon direction can be reconstructed quite precisely. Muon detection is based on ability of muon to penetrate thick absorbers with minor energy losses [17]. The muons interact only electromagnetically with only a small decrease in energy. Due to the size of muon systems ($10^3 m^2$) scintillation detectors of the dimensions 1.6m by 10cm by 10cm are used. This approach of muon detection has the advantage that the
achievable $A_\mu$ and hence data transmission rate does not depend on environmental factors.

2) Look for Cherenkov light radiation [9] produced by fast moving muons in seawater. It allows creating a detector with dimensions that roughly the distance that travels in seawater. Muon detection in a transparent medium, like sea water, can be efficiently achieved by exploiting Cherenkov light, which is emitted along a cone with a constant opening angle, $\theta_c$, in water $\theta_c = 42^\circ$ [14]. The number of photons emitted per unit length of the muon track in the wavelength range 400 - 550 nm, corresponding to the region of maximum transmission in sea water, is $dN/dl \sim 40000 \text{ m}^{-1}$. The number of photons at the detector, $N$, which is a distance, $r$, away from the track is

$$N = \varepsilon_q \exp \left[ -r/\left( \sin \theta_c \lambda \right) \right] a/(2\pi r) dN/dl \tag{10}$$

Where $\lambda$ is the absorption length, $a$ is the detector area and $\varepsilon_q$ is the quantum efficiency of the detector [14], [17]. Setting a trigger threshold of $N = N_t$, we can solve for the distance $r_t$ up to which a muon will yield at least $N_t$ photons. The effective muon detection area $A_\mu$ is then $A_\mu = (r_t)^2 \times \pi$. In order to allow track reconstruction, especially in the presence of backgrounds, it will be necessary to deploy a number, $Q$, of photon detectors, each with area $a$. In this case, the total number of signal photons, $S_p$, will be $S_p = N_t \times Q$ and the total effective photon detection area, $A_p$, will be $aQ$.

Assuming a timing resolution of each detector of $t$ we want each detector $i$ to be no larger than $\delta x = c \delta t$. Conversely, each detector sees the track for no longer than $\delta t$ and thus we have a background suppression of $\delta t^4$. Obviously, the detector area, $a$, can be no larger than $c^2a^2\delta t \pi$. To keep the total number of photons detected constant it will be necessary to increase the number of detectors, $Q$, such that $A_p = aQ = Qc^2\delta t^2 \pi$ stays constant. Also, individual detectors should be spaced no closer than $\delta x$. At the same time, $\delta x$ sets the scale down to which the components of a track vector are known.

If we assume a linear array of photo-detectors with a length $l_p$, then the angular resolution $\delta \theta$ of the array is approximately given by $\tan^{-1} \delta \theta \approx \delta x/l_p$. Since we know that the muon must lie within $\delta \theta$, of the beam direction, there can be, $n_0 = \delta \theta c^2/\delta \theta$. The photon detectors survey an area $A_\mu$ with a maximal resolution of $\delta x$, thus there can be $n_x$ different origins for the muon track $n_x = A_\mu/\delta x^2$.

And finally, there can be different event starting times, $n_t = \delta t^{-1}$. Altogether, there can be $m = n_x n_y n_z$. Different valid muon tracks. For $\delta t = 1\text{ ns}$ and $l_p = 100\text{ m}$, we obtain $m \sim 10^{18}$.

Along each, of this $m$ distinct, possible tracks there can be random fluctuation of stochastic backgrounds from actual photons, radioactive decays or electronic noise. Irrespective of their origin they all share the property of being random and thus are neither correlated in space nor time. The total background is given by $B = 4\pi b f A_\mu$ where $b f$ is the background rate in units of $s^{-1} \text{ m}^{-2} \text{ sr}^{-1}$. The track is seen at each individual photodetector for only $\delta t$, thus we need to be concerned only about background in the window $\delta t$, i.e. we obtain an immediate background suppression of $\delta t^4$ and the effective background, $B_e = B \delta t$.

We next require that the probability of the effective background $B_e$, to fluctuate up to the signal $S_p$ is smaller than $1/ f m^{1}$, thus ensuring that on average there are not more than $1/ f m$ random coincidence events per second happen in the entire detector and we use $f = 1000$. For large $S$ and $B$, the probability can be approximated by a Gaussian and we can solve for $B_e$ as a function of $S$ and obtain $B_e = S^2/(2q^2)$ with $q = \text{erfc}^{-1} \left[ 2/(f m) \right]$ and where erfc$^{-1}$ denotes the inverse of the complementary error function [12].

So far, we have not made use of the photon arrival direction. Reconstruction of the photon arrival directions with a resolution of $\delta \theta$, will result in a background suppression, $\varepsilon_s$, of $\varepsilon_s = \delta \theta^2$. A simple optical system like a lens or mirror can translate the arrival direction of a photon into the position in the focal plane. Finally, the photon background can be as large as

$$b \leq 1.2 \times 10^8 S_p^2 \left( \frac{\text{deg}}{\delta \theta} \right)^2 \left( \frac{ns}{\delta t} \right)^2 \text{s}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \tag{11}$$

Fig. 1: Global distribution of the achievable information capacity. Panel (a) shows the Cherenkov detection scheme during daylight (noon), panel (b) shows the results for the direct detection scheme and panel (c) shows the results for the Cherenkov detection scheme during night. The black $x$ denotes the position of the sender. Land masses are dark gray and the turquoise area indicates missing data on the optical properties of sea water. The areas in olive indicate shallow water with a depth of 25m or less.
without causing a fake muon rate in excess of \(1/f = 10^{-3} \text{ s}^{-1}\). For a given \(b\), we can set the trigger threshold \(N_t\) such that \(S_p\) is sufficiently large for this equation to hold. \(N_t\), in turn, determines, together with \(\lambda\), how far out or at which maximal distance, \(r_t\), a muon can be seen above background and thus sets the size of \(A_\mu\).

**C. DATA ENCODING AND DECODING**

UNC, in this respect, is very similar to deep space optical communications, where very few photons need to carry the largest possible amount of information [15]. This is achieved by using pulse position modulation (ppm), where one unit of time is divided into \(M\) slots and we can freely chose in which of these slots we transmit the pulse. Of course, if enough photons/neutrinos are available we can decide to transmit a number, \(P\), of pulses per unit time. In the context of a muon storage ring, the number of slots is determined by the inverse of the duty factor. Duty factors of the order of \(10^{-4}\) seem feasible, therefore we will take \(M = 2^{14}\). The optimum number of pulses will depend on the available muon event rate. In the context of information theory the above system corresponds, in the absence of backgrounds, to an \(M\)-ary Poisson erasure channel. The capacity of an information channel is the theoretically maximal rate at which information can be transmitted with an arbitrarily small error probability. In practice, a coding scheme is required to achieve good performance. However, research in the last decade or so has produced a number of practical coding schemes which actually can perform very close to capacity. The capacity, in our case, given as a function of \(P\) is

\[
C(P) = \sum_{k=0}^{P} \left(1 - e^{-\frac{P}{k}}\right)^{P-k} \log_2 \left(\frac{M}{P}\right) - \log_2 \left(\frac{M-P+k}{k}\right)
\]

Where \(\epsilon\) is the erasure probability, which for a Poisson process is \(1 - \left(1 - e^{-\frac{P}{k}}\right)^P\) with \(S\) being the number of events per unit time. For a given value of \(M\) and \(S\) we can determine the optimum number of pulses which maximizes the capacity. For \(M = 2^{14}\), the maximum capacity, \(C_m\), can be parametrized as \(C_m = 6.61xS^{0.74}\) bit/s. Using the previous result on \(\phi_t = 2.2 \text{ s}^{-1}\) we obtain a capacity of \(\sim 10\) bit/s even at the antipodes of the sender.

In reality, most neutrino sources have a range of energies which will tend to “wash out” the distribution. To investigate the changes to the amplitude and oscillation length, we explore two possibilities for neutrino energy distributions: a narrow band distribution, and a wide band distribution. In the first case, we assume that the neutrino momentum is well-defined, that is, \(\Delta p = p < 5\%\). The neutrino energy distribution is shown in the Fig.1 while the resulting oscillation probability is shown as a function of length in Fig.2. The oscillation as a function of length \(P_{\nu\mu \rightarrow \nu e}(L)\) is calculated by convoluting the energy distribution \(f(E)\) in Fig. 1 with the oscillation probability \(P_{\nu\mu \rightarrow \nu e}(L)\).

\[
P_{\nu\mu \rightarrow \nu e}(L) = \int_0^L P_{\nu\mu \rightarrow \nu e}(L, E) f(E) dE
\]

The energy distribution is described by the following function:

\[
\frac{dN}{dE} = E^2 \left(1 - \frac{2E}{3E_{\text{max}}}\right)
\]

Where \(E_{\text{max}}\) is 52.8 MeV for muon decay. Once again, convoluting this energy distribution with \(P_{\nu\mu \rightarrow \nu e}(L)\) we obtain the oscillating function as shown in Fig.3 and Fig.4. Notice that both the amplitude and the peaks of the oscillation \(P_{\nu\mu \rightarrow \nu e}(L)\) are shifted [12], [13], [16].
One of the principle advantages of ppm is that it is an M-ary modulation technique that can be implemented non-coherently such that the receiver does not need to use a phase-locked loop (PLL) to track the phase of the carrier. This makes it a suitable candidate for communication systems, where coherent phase modulation and detection are difficult and extremely expensive. Decoding pulses to deduce basic information requires data like particle spin, mass, lepton number, baryon number, parity and other quantum numbers. PPM technique leads to small, light-weight receiver/decoder units.

IV. CONCLUSION

The communication is one of the most important aspects of the robotic systems. In this paper we have described an approach to fulfil the basic requirements to use neutrinos as a means of communication in deep sea. We have demonstrated that a neutrino beam from a muon storage ring can be detected by sensors mounted on the hull of an underwater robot. This in principle would allow establishing a communication link at speed and depth with data rates in the range from 1-100 bit/s which improves current ELF data rates by 1-3 orders of magnitude and is similar to data rates offered by VLF. The efficiency of proposed approach has been discussed extensively.

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