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ARTICLE

Underwater Communication with Blue Light

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There are strong demands to explore unknown frontiers in the ocean and below the seabed from the viewpoints of understanding the global environmental change and climate crisis [The Intergovernmental Panel on Climate Change, 2014], using various marine resources sustainably [Fisheries and Oceans Canada, 2019], studying earthquakes and volcanic activities in sea areas [Špičák, A., et al., 2013] and elucidating the history of life on earth [Japan Agency for Marine-Earth Science and Technology, 2019] and so on.
Since electromagnetic waves are attenuated rapidly while the waves travel through the sea water [Talley, L., et al., 2011], long-distance communications like mobile phones cannot be expected in the sea. Therefore, in oceanographic surveys, acoustic communication has been used for communication. However, the propagation speed of sound is about 1,500 m/sec in the water, which is very slow compared to that of electromagnetic waves including light (approximately 200 million m/sec in water). Applicability of electromagnetic waves to communication in the ocean has been investigated [Karagianni, E.A., 2015]. The adverse effects of chlorophyll, turbidity (cloudiness) and marine snow were pointed out and the importance of development of wireless technology were recommended [Moore, C., et al., 2009; Kwasnitschka, T., et al., 2016; Sawa, T., et al., 2019].

INTRODUCTION

The study of wireless visible light communication started in the 1960s when lasers with high optical densities were invented [Sawa, T., et al., 2019]. However, it is not realized because laser is attenuated by suspended particles like marine snow and light alignment is difficult on unstable ships and underwater vehicles due to ocean waves and currents. By recent progress of light-emitting diodes (LED) and laser diodes (LD), a possibility of underwater wireless visible light communication has been actively discussed [Sawa, T., et al., 2019]. However, only a few experiments on the underwater wireless visible light communication in the ocean have been carried out and the experimental evidence is still required.

In Fukushima Daiichi nuclear power station in Japan, sea water was supplied to cool the nuclear fuels when they lost all electric power supply during its accident in 2011. It is considered that part of nuclear fuel debris was fallen into the primary containment vessel and is now in the water containing the salt [Global Research Safety, 2020]. In the decommissioning of Fukushima Daiichi nuclear power station, the development of technology to recover the debris safely is a top priority [Asama, 2019]. A challenge is to develop the communication devices with high radiation tolerance.

The purpose of this research is to study the effects of the visible light colour, the presence of chlorophyll and marine snow, the turbidity and the light link configuration on the visible light communication through the salt water and to elucidate a possibility of underwater wireless visible light communication in the ocean. In addition, the applicability of underwater wireless visible light communication to the decommissioning in Fukushima Daiichi nuclear power station was investigated.

The i-phone, the Nintendo switch, the speaker and the AA batteries used were on hand. The distilled water and the sodium chloride (reagent grade) were provided from McMaster University. The pool salt was purchased at Canadian Tire. The other materials were purchased from amazon.ca.

MATERIALS LIST

Table 1 summarizes a list of materials prepared in this study. (on page 2)

EXPERIMENTAL METHOD AND DESIGN

DESIGN, ASSEMBLY AND PERFORMANCE VERIFICATION OF TRANSMITTER AND RECEIVER

The transmitter with the LED and the receiver with the photodiode were independently designed and assembled. In the design, the electric circuit developed by Ito et al. [Ito, T., et al., 2018] was referred. The circuits of transmitter and receiver, based on the suggestions by Sasamori [Sasamori, 2020], is shown in Supplemental Material S-1. The blue, green, red or white LED light was used as a carrier wave. Because the size and transmission speed of information/data were moderate, the music recorded in an i-phone or Nintendo switch was used as the information/data wave.

Three quartz cuvettes (5.0 cm optical length each) were arranged in a straight line (total optical length = 15.0 cm) between the transmitter and the receiver. The sound level of music played back from the speaker in the receiver was measured by the noise monitor. It was confirmed that only the LED light passing through

Table 1 Summarizes a list of materials prepared in this study.

Item	Number	Item	Number	Item	Number
breadboard	2	condenser (10 μF)	2	jack plug cable	1
LED (blue)	1	resistance (100 kΩ)	2	battery box	2
LED (green)	1	resistance (4.7 kΩ)	1	battery snap	2
LED (red)	1	resistance (220 Ω)	1	AA battery	8
LED (white)	1	transistor	1	jump wire	14
photodiode	1	stereo mini-jack	2	quartz cuvette (optical length: 50 mm)	3
quartz cuvette (optical length: 10 mm)	4	distilled water	-	Water sampled from Lake Erie	500 mL
speaker	1	pool salt	6.3 kg	Water sampled at Halifax	200 mL
i-phone and Nintendo switch	1 each	sodium chloride (reagent grade)	500 g	Water sampled at Vancouver	200 mL
noise monitor	1	Chlorop hyll (solid)	100 g	Water sampled at Fukushima, Japan	200 mL
lab lift table	5	turbidity standard solution (10 NTU)	240 mL	Water sampled at Guam, the USA	200 mL
tap water	-	marine snow (4,000 ppm)	250 mL	Portable mini radio	1

Figure 1 Experimental set-up (a) and measurement in darkroom (b).

the cuvettes was measured by the photodiode. Whether the visible light can be transmitted through the air, the distilled water and the salt water was studied with and without modulation of music. Measurements were conducted in the darkroom to avoid the background lights. The experimental set-up and the image of measurement in the darkroom are illustrated in Figure 1.

The physical properties of sea water are usually studied by salinity [Talley, L., et al., 2011]. The average value of salinity of sea water around the world is about 3.5 % [Talley, L., et al., 2011]. Therefore, salt water with 3.5 % salinity was used in this study.

EFFECT OF COLOUR OF LED

The LED, quartz cuvettes (15 cm) and photodiode were confirmed to be lined up in a straight line. Firstly, neither distilled water nor salt water was placed in the cuvettes. The music was modulated with the LED light. The sound level was measured for all four LED light colours. The sound level in the air was set to the reference value for each colour (S0). Then, the sound level was measured (S), while the optical length of the quartz cuvette changed from 1 cm to 19 cm in the presence of distilled water or salt water in the cuvettes. The ratio of the sound level at various optical length to the reference value (S/S0), defined as attenuation in this study, was calculated. The light which gave the highest value of S/S0 and the highest sound level was considered to be the most preferable colour for underwater communication. The average sound level for 5 seconds was measured at least 50 times (same to all following measurements).

EFFECT OF CHLOROPHYLL, CLOUDINESS AND MARINE SNOW ON COMMUNICATION

Three quartz cuvettes were arranged in a straight line (total optical length = 15 cm) between the transmitter and the receiver. The sound level through the clean salt water (no chlorophyll, turbidity nor marine snow) was measured for four LED lights. The sound level was set to the reference value.

The typical concentration range of chlorophyll in the ocean is from 0 to 10 ppb and the average concentration is 0.5 ppb [Sawa, T., et al., 2019]. The salt waters with various chlorophyll concentrations (0.01, 0.05, 0.1, 0.5, 1, 2, 5 and 10 ppb) were prepared. The typical value range of turbidity is from 0 to 4 NTU and the average value is 0.6 NTU [Sawa, T., et al., 2019]. The salt waters with various turbidity (0.01, 0.02, 0.05, 0.1, 0.2, 0.6, 1, 2 and 4 NTU) were prepared. The typical concentration range of marine snow is from 0 to 200 ppm and the average concentration is 30 ppm [Lampitt, R.S., et al., 1993]. The salt waters with various marine snow concentrations (1, 5, 10, 30, 50, 100 and 200 ppm) were prepared.

The salt water containing the chlorophyll, turbidity or marine snow was added into the three cuvettes. The music was modulated with the LED light. The effects of chlorophyll, cloudiness and marine snow were studied by measuring the sound level.

EFFECT OF LIGHT LINK CONFIGURATION ON COMMUNICATION

The optical configuration was the same as above. The clean salt water was added into the three cuvettes. The relative position of the receiver against the transmitter changed up and right. The positions where the sound level of music was smaller than 50 dB for more than 1 minute was measured. As mentioned later, since the blue LED light was found to be most promising for underwater wireless visible light communication, only blue LED light was used (this was same hereinafter).

COMMUNICATION IN LAKE AND SEA WATERS The optical configuration was the same as above. The sound level through the clean salt water was measured for blue LED light to set to the reference value. The average sea water, which contained the average concentrations of chlorophyll and marine snow and the average value of turbidity, and the worst sea water, which contained the highest concentrations of chloro-phyll and marine snow and the highest value of turbidity, were prepared. The waters sampled from Lake Erie, the Atlantic Ocean (Halifax in Canada) and the Pacific Ocean (Vancouver in Canada, Fukushima in Japan, and Guam in the USA) were also used. The following procedure was the same as above except for the worst sea water. For the worst sea water, the water length was set to 5 or 10 cm.

POSSIBILITY TO USE IN FUKUSHIMA DAIICHI NUCLEAR POWER STATION

The optical configuration was the same as above. The sound level through the clean salt water was measured for blue LED light using the non-irradiated transmitter and receiver. The sound level was set to the reference value. The transmitter and the receiver were irradiated by Taylor Radiobiology Source at McMaster University (Cs-137; 1, 10 and 100 Gy). The clean salt water was added into the three cuvettes. The following procedure was the same as above.

RESULTS AND DISCUSSION

PERFORMANCE VERIFICATION OF TRANSMITTER AND RECEIVER.

The sound level when the LED light passed through the air, the distilled water and the salt water in the absence of music are summarized in Supplemental Material S-2. It was confirmed that the visible lights were attenuated by the distilled water and the salt water, compared to the air, but that they could travel through both waters. This suggests that visible light can be used for underwater communication.

Furthermore, the intensity of lights after 15 cm transmission was practically the same among all four LEDs. Therefore, the absolute value of sound level (dB) could be used directly for the comparison.

Moreover, it was found that the information of music could be transmitted through distilled water and the salt water and that the music was clearly played back by the speaker (Supplemental Material S-3).

EFFECT OF COLOUR OF LED

Dependence of the sound level on saltwater length is summarized in Table 2. Blue and white lights were confirmed to be preferable for the underwater wireless communication.

The dependence of attenuation on water length by blue LED light is illustrated in Figure 2. The sound level seemed to be linearly attenuated against the water length. The degree of attenuation of blue light in salt water was smaller than the other three lights. The solid line in Figure 2 represents the fitting result obtained by the least squares method for the saltwater data assuming linearity.

If that the sound level with 60 dB (attenuation = 0.838) is required for the communication due to the noise of current and wave of ocean, the blue LED light can travel about 30 cm through salt water. The light intensity of the blue LED used in this study was 20 cd. One of the strongest light power of portable LED is approximately 8600 cd [Interesting Engineering, 2019]. If the communication distance is proportional to the light intensity, 129 m transmission in salt water is possible using 8600 cd LED light. If the sound level with 50 dB is enough, 220 m communication is possible.

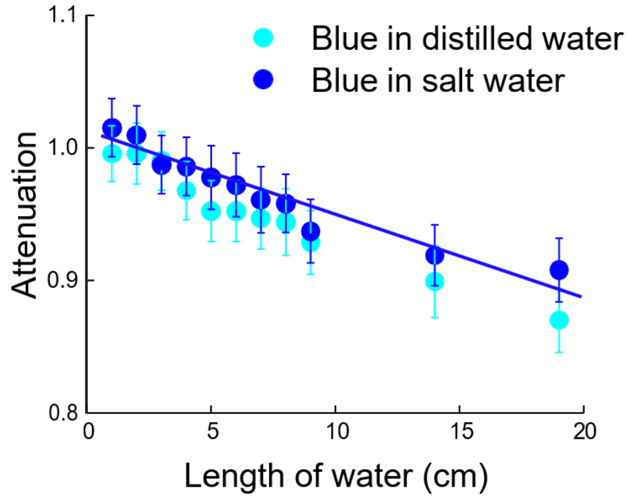

Figure 2 Dependence of attenuation on length of distilled water and salt water for blue LED light. A solid line represents fitting result by least squares method for saltwater data.

Table 2 Dependence of sound level of four LED lights on saltwater length (unit: dB)

Length (cm)	1	2	3	4	5	6
Blue	72.7 ± 0.8	72.3 ± 0.8	70.7 ± 0.7	70.6 ± 0.7	70.0 ± 0.9	69.6 ± 1.0
Green	68.1 ± 1.5	67.6 ± 0.7	65.1 ± 0.7	65.0 ± 0.9	65.0 ± 0.7	64.1 ± 0.9
Red	67.8 ± 0.8	66.5 ± 0.7	65.5 ± 0.7	65.2 ± 0.7	64.2 ± 0.8	63.8 ± 0.8
White	72.8 ± 0.8	71.9 ± 0.8	71.9 ± 0.8	71.4 ± 0.8	71.0 ± 0.8	70.5 ± 0.8

Length (cm)	7	8	9	14	19
Blue	68.8 ± 1.0	68.6 ± 0.6	67.1 ± 0.8	65.8 ± 0.7	65.0 ± 0.8
Green	61.7 ± 0.8	61.7 ± 0.7	61.1 ± 0.6	60.7 ± 0.6	58.9 ± 0.8
Red	63.6 ± 0.8	62.8 ± 0.7	62.2 ± 0.8	62.1 ± 0.7	59.4 ± 1.5
White	70.2 ± 0.7	69.4 ± 0.8	69.3 ± 0.8	64.8 ± 0.8	64.6 ± 0.8

EFFECT OF CHLOROPHYLL, CLOUDINESS AND MARINE SNOW ON COMMUNICATION

Figure 3 shows the dependence of attenuation on the concentration of chlorophyll, the turbidity and the concentration of marine snow.

Figure 3 (a) showed that the degree of attenuation for red and white was large and that for blue and green was small. The degree of attenuation for green was smaller than that for blue, but the difference was very small. Colour of chlorophyll is green and therefore red and probably yellow lights should be preferably absorbed due to complementary colour relationship, but green light is not. The results obtained here are consistent with complementary colour relationship. From Figure 3 (b), the attenuation decreased linearly with the turbidity up to 1 NTU, and then the attenuation was independent of the turbidity for all four LED colours. The degree of attenuation for blue LED light was the smallest. Regarding the effect of concentration of marine snow, the music was clearly heard up to 50 ppm marine snow but could not be heard at 100 ppm and 200 ppm. Since the average concentration of marine snow is 30 ppm and the highest concentration is 200 ppm, the concentrations of marine snow in many oceans around the world are smaller than 30 ppm. The degree of attenuation below 30 ppm in Figure 3 (c) were similar to all four LED lights used, suggesting that all visible LED lights can be used to communicate in many oceans.

From these results and the result of the effect of colour, it is considered that underwater wireless visible light communication in the ocean is possible and blue light is the best colour.

EFFECT OF LIGHT LINK CONFIGURATION ON COMMUNICATION.

The angles on which the receiver could no longer catch the music were 47° for the up and 34° for the right side. Now, let us suppose that we are making the 100 m distance communication in the ocean. Angle 34° corresponds to 59.3 m of relative travel distance of the receiver to the transmitter. Considering that the velocities of current and wave around the world (5 cm/s to 200 cm/s) [Lumpkin, R. and Johnson, G.C., 2013], we have 30 seconds (200 cm/s) to 20 minutes (5 cm/s) before the communication is lost.

Considering that the design-basis accident such as loss of coolant accident can be safely managed within 30 seconds in nuclear power stations [Buschman, F.X. and Meholic, M.J., 2019],

Table 3 Sound level and attenuation of blue LED light in various waters

Water Type	Lake Erie	Atlantic Ocean (Halifax)	Pacific Ocean (Vancouver)	Pacific Ocean (Fukushima, Japan)
dB	80.8 ± 1.2	79.1 ± 1.6	78.5 ± 1.5	78.9 ± 1.0
Attenuation	0.999 ± 0.024	0.978 ± 0.027	0.970 ± 0.027	0.975 ± 0.023
	Pacific Ocean (Guam, the USA)	Average Sea Water	Worst Sea Water (5.0 cm)	Worst Sea Water (10.0 cm)
	79.9 ± 1.4	78.5 ± 1.7	60.6 ± 1.8	47.7 ± 2.7
	0.988 ± 0.026	0.970 ± 0.028	0.709 ± 0.041	0.573 ± 0.050

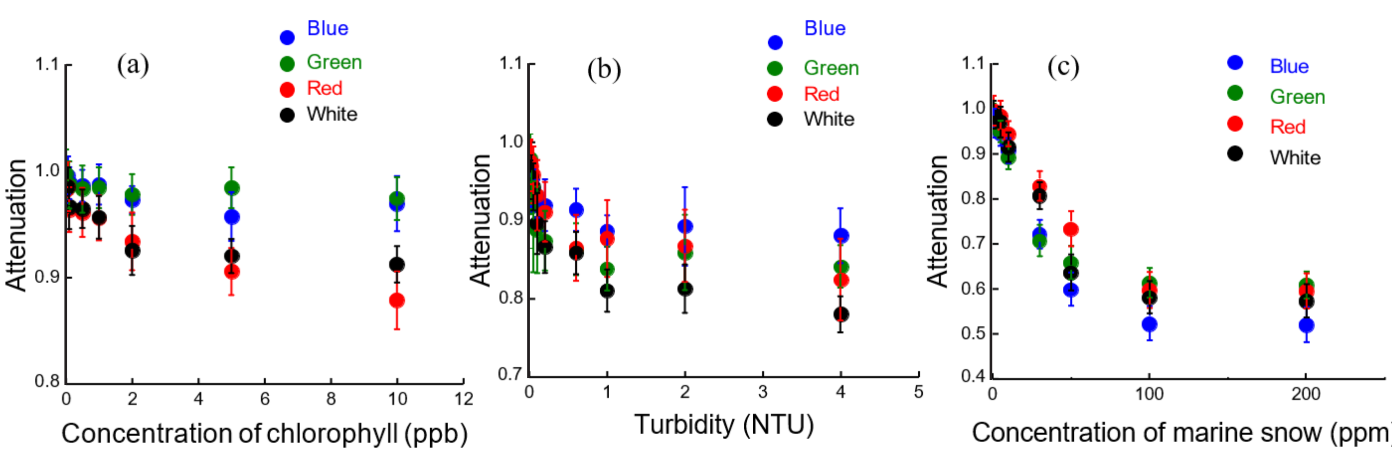

Figure 3 Dependence of attenuation on chlorophyll (a), turbidity (b) and marine snow (c).

we can control the system to continue the communication under any dynamic conditions of current and wave in ocean.

COMMUNICATION IN LAKE AND SEA WATERS

The sound level and attenuation of blue LED light in the waters taken from the Lake Erie and the Atlantic and Pacific Oceans and the average and worst sea waters synthesized are summarized in Table 3. The music was clearly able to be heard in all waters except the worst sea water. Underwater wireless visible light communication with blue LED light can be considered to be used in the real ocean.

POSSIBILITY TO USE IN FUKUSHIMA DAIICHI NUCLEAR POWER STATION

The radiation dose dependence of sound level and attenuation of blue LED light is summarized in Table 4. Up to 10 Gy, the reduction of sound level and attenuation was not large. At 100 Gy, the sound level was small but it was still able to be heard clearly. The development target for radiation tolerance is 200 Gy [Arai, 2020]. In this study, the transmitter and the receiver were directly irradiated. However, in real use, the transmitter and the receiver will be covered by the radiation shielding materials. Although the outside shielding material is exposed to 200 Gy, the actual radiation exposure of the transmitter and receiver inside of shielding material may be much smaller than 200 Gy. Hence, the concept of underwater wireless communication with blue LED light studied in this study can be considered valuable to the safe decommissioning of Fukushima Daiichi nuclear power station.

CONCLUSIONS

This research examined whether underwater wireless visible light communication could be used in the ocean. The transmitter with an LED light (blue, green, red or white) and the receiver with a photodiode were designed, assembled and used for the experiments. The effects of the colour of LED light, the concentrations of chlorophyll and marine snow and the degree of cloudiness (turbidity) in salt water were measured. From the sound level and the degree of attenuation, blue LED light was found to be the best colour for the underwater wireless visible light communication in salt water. From the light link configuration test, it was also found that visible light communication using blue LED light could be controlled in the dynamic wave and current of the ocean. Finally, it was demonstrated that the underwater wireless visible light communication could be conducted in the waters sampled from Lake Erie, the Atlantic Ocean and the Pacific Ocean. Therefore, underwater wireless visible light communication is possible and blue light is the most promising for it.

The applicability of underwater wireless visible light communication with blue LED light to the decommissioning in Fukushima Daiichi nuclear power station (F-1) was also studied using the irradiated transmitter and receiver and the salt water. It was suggested that underwater wireless visible light communication can be used for safe decommissioning in F-1.

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Table 4 Dependence of sound level and attenuation on radiation dose

Radiation (Gy)	0	1	10	100
dB	76.5 ± 1.1	72.3 ± 1.0	70.0 ± 1.0	54.6 ± 1.0
Attenuation	—	0.944 ±0.020	0.915 ±0.021	0.714 ±0.025

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My name is Kibo Nagasaki. I go to Oakville Christian School and currently in grade 8. When I go to school, the subjects that I look forward to doing the most are science, mathematics and PE. Aside from academics, I also go to my track and field club, badminton club, violin and go to Japanese school. This is my first science fair and I was happy to hear that my project received the high score at the Bay Area Science and Engineering Fair and have this opportunity to publish my project in this amazing scientific journal.