Underwater Electromagnetics and Its Application to Unmanned Underwater Platforms

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***Abstract*-Electromagnetic wave (EMW) has improved human life and is then essential technology for mankind, but it is basically useless in the sea. Although acoustic wave is the most effective means for underwater applications, it has disadvantages of long propagation delay and narrow bandwidth. Meanwhile, evolution of electronics and information technology improves ocean platforms such as buoys, landers, unmanned surface vehicles, and unmanned underwater vehicles as well as sensors. The upgrading of ocean platforms leads us to improve efficiency and reduce the cost of ocean research. To achieve practical unmanned platforms, we should build a seamless land-to-underwater wireless network for monitoring all platforms.**

Since 2002, we have restudied underwater EMW propagation and its applications for surface-to-sea communication, sea-to-sea communication, and underwater telemetry. The work includes the basic study of medium frequency (MF) to high frequency (HF) wave underwater propagation, the basic study of deep-sea optics, and the application study of underwater laser. Some test results show that there might be a low damping mode of HF wave propagation in the sea. It was determined that a few watt class blue-green laser propagates underwater up to hundreds meters. A laser ranging system was prototyped and carried sea trials. In the conference, we would like to report on progress of the studies including some test results and show examples of their application to underwater platforms in the future.

I. INTRODUCTION

In recent years, exploration and mining of underwater mineral resources are focused for lasting economic growth in Japan. Unmanned underwater platforms (UUPs) including unmanned underwater vehicles (UUVs) are expected as tools for exploration and mining because their utilization will result in reducing operation cost and enabling wide area survey.

The building of seamless land-to-underwater wireless network is a key process to establish a practical UUPs operation for the exploration. In order to perform the exploration safety and certainly, monitoring of UUPs, in particular movable platforms or UUVs, in operation will be required. Surface-to-underwater communication achieves a real time monitoring or controlling of UUVs from a ship or a land station. Underwater-to-underwater communication establishes new schemes of operation such as communication between UUVs or an UUV and a moored platform. Depending on the intended use of the communication, many kinds of service range and rate will be necessary. An UUV, for example, would take large volumes of data such as high resolution images of sonars or/and still cameras. An UUV would cruise around and collects data from a seafloor station. A multi-UUV configuration will achieve cost reduction on the operations, and thus highly efficient exploration. New practical underwater communication methods in addition to traditional acoustic communication are demanded to perform new operations mentioned above because acoustic one has disadvantages of long propagation delay, narrow bandwidth, and multi pass-broad directivity trade-off.

We have been studying underwater electromagnetic communication including land-to-sea surface communication since 2003. The report digested of the study up to 2010 was presented [1]. A dozen Mbps communication between a land a ship was carried out and a multi-high definition TV transmission was then achieved [2]. A remote control test of an autonomous underwater vehicle was also done successfully [2]. We measured underwater laser propagation characteristics and understand that underwater laser will be valuable in the range up to about 100 m [3]. We achieved development of an underwater laser beam alignment technique [3]. A laser communication system with range up to 100m and rate of over 100 Mbps is considered by our group. Ambalux corporation already produces an underwater laser transceiver ranging 40m with the 10 base interface [4]. On the other hand, development of a radio wave communication/telemetry system of practical use is less-advanced because of difficulties of theories and experiments. In this paper, we report some results of our current study on underwater HF wave propagation and give discussion.

II. STUDY ON UNDERWATER RADIO-WAVE COMMUNICATION

A. *Current Status in Underwater Communication in The World*

We have the common sense to understand that radio wave communication in the sea water is impossible due to exponentially-decaying of electromagnetic waves underwater. In fact, you can use it in frequency of up to about 100 kHz. There are some commercial models in this band. WFS Technologies [5] produces two types of RF modems: a short rang mode, 100 kbps up to 15 m range and a long range model, 100 bps up to 200 m range. Some research institutes [6] are currently conducting development of super short range-high

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speed communication in frequency of around a few GHz. In our applications, a mid-range (about 100 m) and mid-rate (about 100 kbps) communication will be required. Such RF modem does not exist.

Many researchers have carried out experimental research of underwater propagation up to HF band for more than 50 years. It would be surprising that their data of propagation attenuation measured around HF band are widely distributed. This distribution is usually treated as measurement error or is caused by lateral waves. Lucas and his team have taken an interest in the distribution, reported [7, 8] that the oscillation of H_2O molecules can transmit HF waves despite energy absorption by other molecules.

B. The First Experiment of HF Waves propagation in JAMSTEC

To confirm their model, we first carried out a HF propagation experiment at the pier in JAMSTEC. We made a set of underwater dipole antennas (Figure 1) by reference to the antenna proposed by Lucas. The antennas were roughly matched at frequency of 14 MHz. An armature radio transceiver was used as the signal source (TX) which was set at frequency of 14 MHz and output power of 10 Watts. The receiver (RX) was a spectrum analyzer. Both were set on the pier. Antennas were connected with the TX and the RX via 20 meters-coaxial cables. Figure 2 shows the experimental set up. Both of the antennas were set perpendicular to the pier. Distance between the dipole antennas was changed from 0.1 m to 20 m. The graph of received power versus distance is shown in Figure 3. In the figure, the solid and broken red lines denote the background noise measured and the electromagnetic coupling between the TX cable and the RX cable, respectively. The calculated result by an FDTD simulation by assuming the uniform and isotropic background medium is also plotted. The calculated data is rapidly dumped as expected. On the other hand, the dumping curve of the receiving power has a gradual slope than that of the calculation, and then its slope almost flattens over 1 meter. This result would be slightly matched with Lucas's one. But this experiment would include measurement errors caused by the others propagation paths such as a sediment path and a pier wall path.

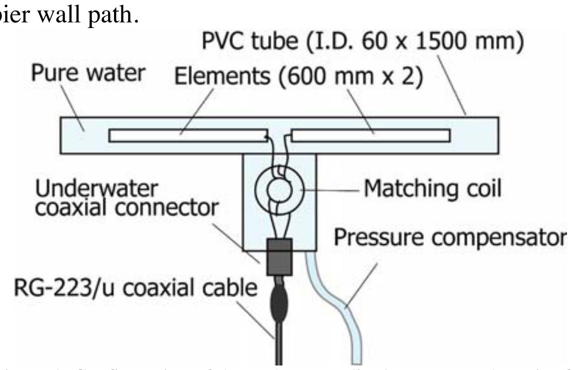

Figure 1. Configuration of the underwater dipole antenna. The pair of antenna elements is immersed in pure water.

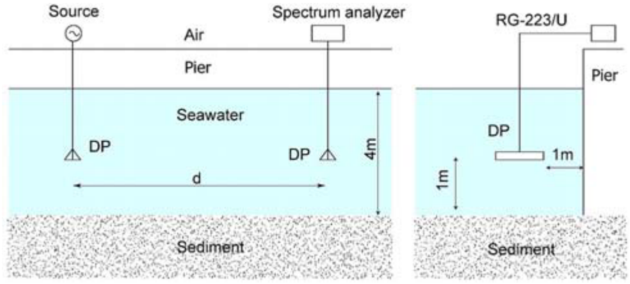

Figure 2. Experimental set up for the HF wave propagation measurement. Left: front view and right: side view.

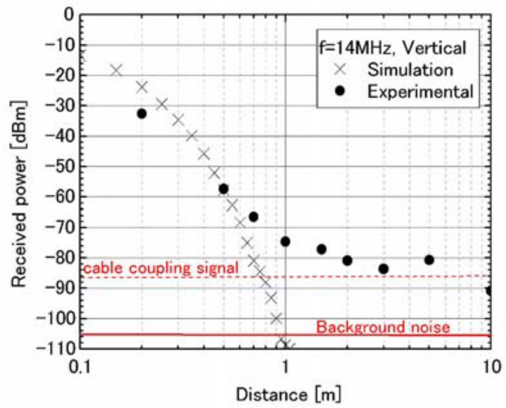

Figure 3. The first experimental result of the underwater HF wave propagation at the pier of JAMSTEC. The closed circle and the cross denote the measured data and simulated one, respectively.

C. Experiment in Open Sea

In order to remove the error by the multipath, we tried an experiment in the open sea. The dipole antennas developed in the first experiment were used. A signal generator, a power amplifier with gain of 30 dB, a 3-dB directional coupler (DC), and a spectrum analyzer (SA) were prepared as TX. The DC and the SA were used for monitoring the reflection signal caused by un-matching, because the antenna was matched at 14MHz only. The transmitting power of 10 Watts was supplied to the antenna via a 40 meters-coaxial cable. The receiver is separated into the ship-side part and the underwater part. Both parts are connected via an optical fiber cable for electrical isolation. The underwater part consists of a preamplifier, a handheld spectrum analyzer (FSH-3 produced by Rohde-Schwarz), an optical transceiver, and a compass, which was used for determination of azimuth angle of the antenna. The ship-side part consists of a controller and an optical transceiver. The controller can remotely control the spectrum analyzer and save data measured.

The open sea experiment was carried out using the research vessel, Kairei in Sagami Bay, Japan. The water depth was about 1000 meters and the depth of antennas was about 10 meters. The frequencies measured were at 1, 14, and 20 MHz. Distance between the antennas was changed from 0.1 m to 2 m. The TX antenna was fixed to the ship with three ropes. The azimuth angle of the RX antenna was adjusted by a rope. The experimental condition was bad because there was a strong sea current and thus the antenna position and angle were unstable. This resulted in reliability degradation of data measured. The underwater HF wave propagation data obtained are shown in Figure 5 and 6. The background noise level is -125 dBm. In this experiment, we could not obtain the data denoting the same tendency of the first experiment. The received power was not observed over 1 meter.

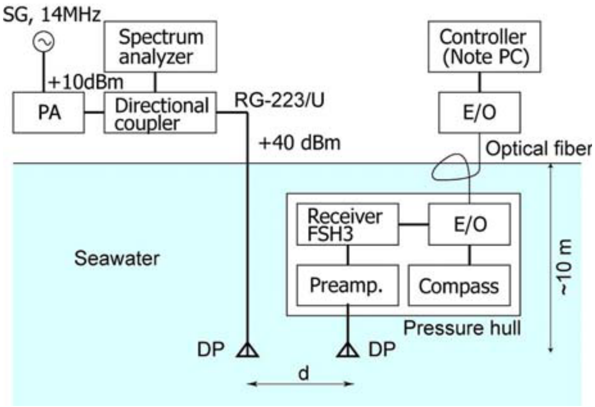

Figure 4. Experimental set up for the open sea measurement.

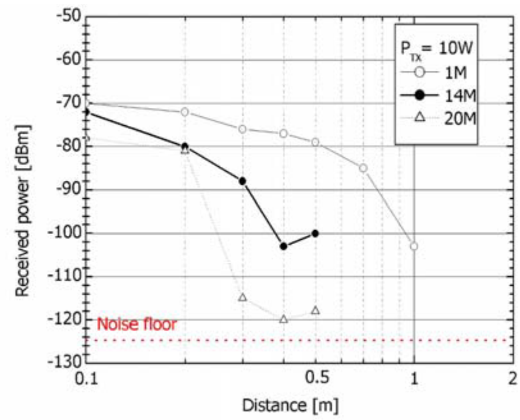

Figure 5. The distance dependence of the underwater propagation.

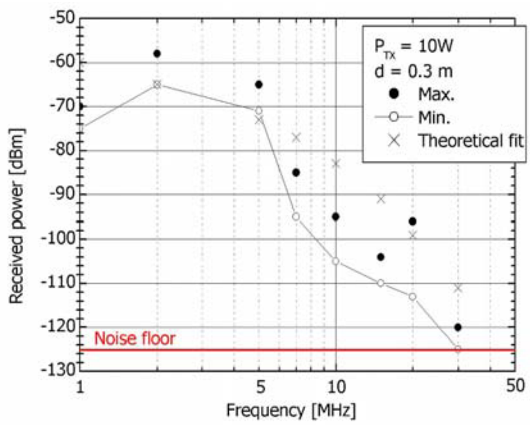

Figure 6. The frequency dependence of the underwater propagation. The cross denotes theoretical attenuation normalized at frequency of 2 MHz.

Figure 6 shows the frequency dependence. The closed and open circles show the maximum and the minimum value of the data, respectively. The theoretical attenuation is also plotted. Although the data are widely spread within 20 dB, the tendency of decay of the measurement data is similar to that of the theory at distance of 0.3 meters. The reliability of this experiment is low but the tendencies of all measured data are roughly coincide with the traditional electromagnetic theory.

D. *Laboratory Experiment*

We obtained different results by the previous experiments. It is the best way to perform a precise experiment in the open sea preparing a rigorous measurement system like a open site for EMC measurement, but it would not be easy to built the experimental system.

In order to perform a precise experiment, we developed a laboratory experimental cage as illustrated in Figure 7. This Faraday cage consists of an aluminum tank, an aluminum top, and an acrylic tank which separates into the buffer layer and the propagation layer. The inner tank can be removed if it is not used. Two underwater connectors are installed on the both side of the aluminum tank. Antennas are set in each buffer layer as shown in Figure 8. The measurement system is symmetrically assembled. A network analyzer measures transmission characteristics and impedance characteristics. We prepared two types sets of insulated antennas: a set of dipole antennas and of loop antennas (Figure 9). Each antenna has a dedicated matching circuit.

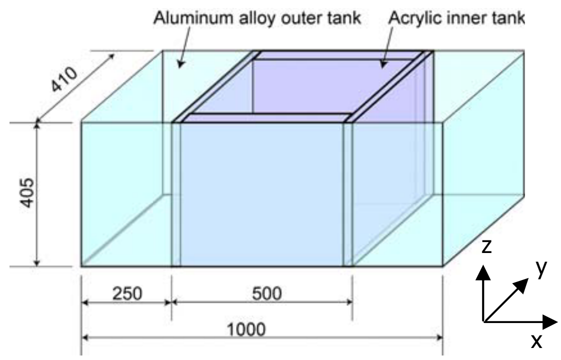

Figure 7. A Faraday cage for the underwater HF wave experiment.

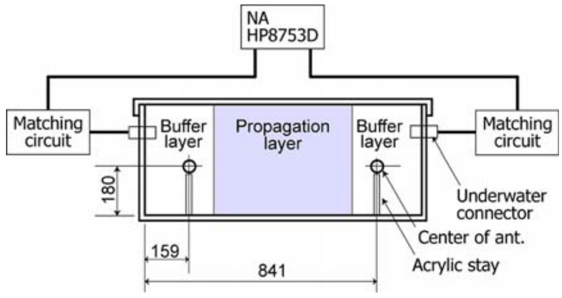

Figure 8. The set up of the experimental apparatus.

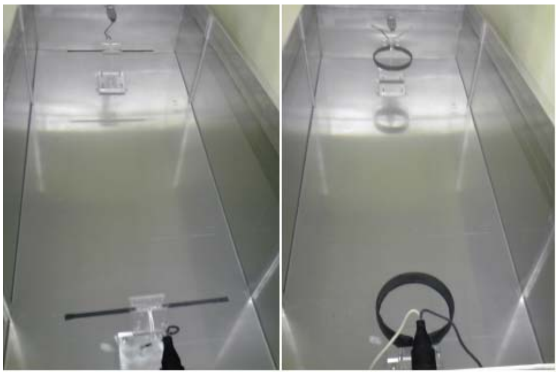

Figure 8. The antennas installed in the outer tank without the inner tank. Left: the dipole antennas, and right: the loop antennas.

In order to adjust the antennas, we first measured s-parameter of input impedance (S11) of each antenna. Figure 9 shows the S11 of the dipole antenna immersed in the tap water. We choose center frequency of 40 MHz for the observation because the cut off frequency of the tank (TE10 mode) is about 40 MHz with the tap water. The sweep frequency range is set between 1 MHz and 100 MHz. We measured transmission characteristics (S21) of three types of configurations as listed in Table I and their results with the dipole antennas are shown in Figure 10.

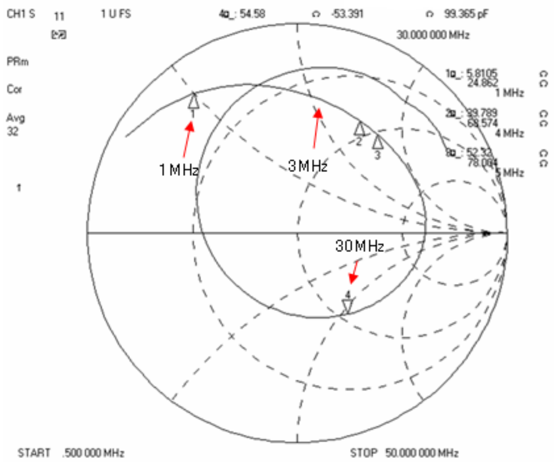

Figure 9. S11 characteristic of the dipole antenna immersed in the tap water in the outer tank.

TABLE I
EXPERIMENTAL CONFIGURATIONS.

Type	Configurations		
	Buffer layer(L)	Propagation layer	Buffer layer(R)
a	Tap water	Tap water	Tap water
b	Sea water	Sea water	Sea water
c	Tap water	Sea water	Tap water

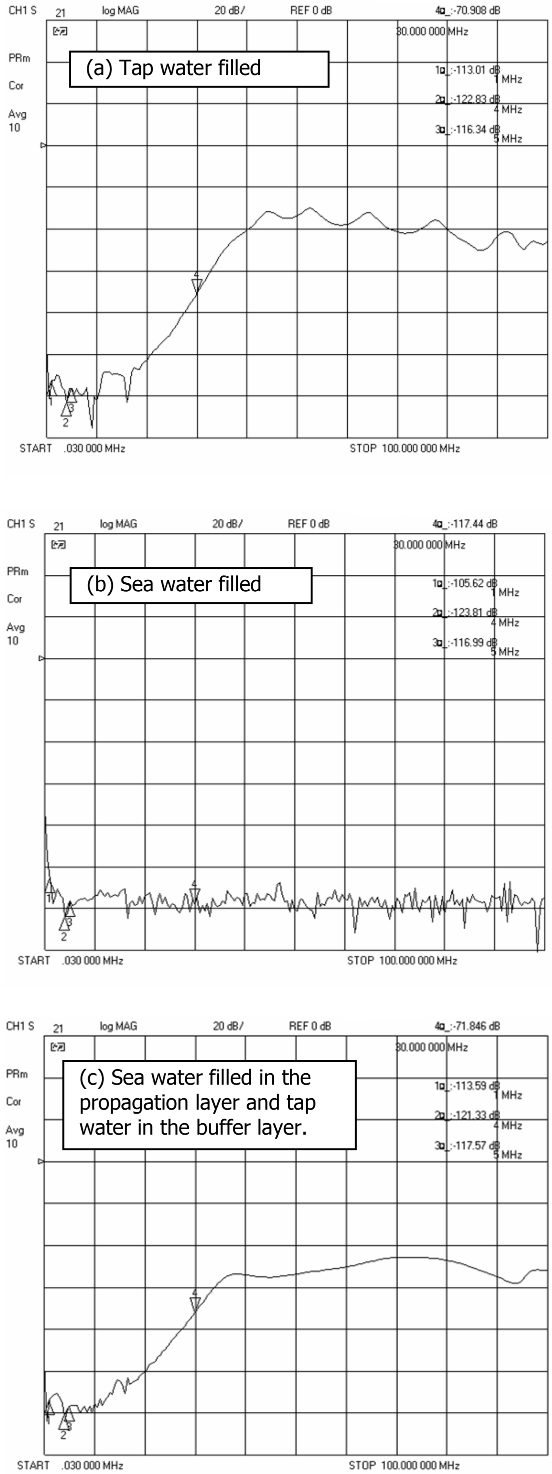

Figure 10. The frequency dependences measured in three types of configuration. Vertical axis and horizontal axis denote the transmission characteristic and frequency, respectively.

If each layer is empty, we cannot observe receiving signals because of the cut off. When whole tank is filled by the tap water (in case of type-a), the cut off becomes lower and then receiving signals can be observed. It can be seen in Figure 10 (a). When the tank is filled by the sea water (in case of type-b), the cut off decreases but we never see receiving signals due to large attenuation of the HF waves. The attenuation at frequency of 40 MHz is calculated to be 220 dB. Therefore, no signals are detected (Figure 10 (b)). The amazing result can be seen in Figure 10 (c). In the test configuration, the propagation layer is filled by the sea water (the specific gravity of 1.030 and water temperature of 15 degrees) of which attenuation is estimated to be 110 dB around 40 MHz. The trend of the transmission curve of the type-c is, however similar to that of the type a. The difference of the signal level between the type-a and the type-c is only 20 dB at 40 MHz. It cannot be explained by the traditional model of the sea water electromagnetics. The same data was obtained by the experiments using the loop antennas. To confirm this, FDTD simulations were performed for the both types. The transmitting antenna and the receiving antenna are located at x = 0.159 m and 0.841 m, respectively. In case of type-a, the damping of the electric field of 50 MHz at the receiving point is smaller than that of 30 MHz due to the cut off frequency. In case of type-c, the damping of the electric field at the receiving point is lager at whole frequency band due to absorption of the sea water. This simulation results are coincident with the traditional theory.

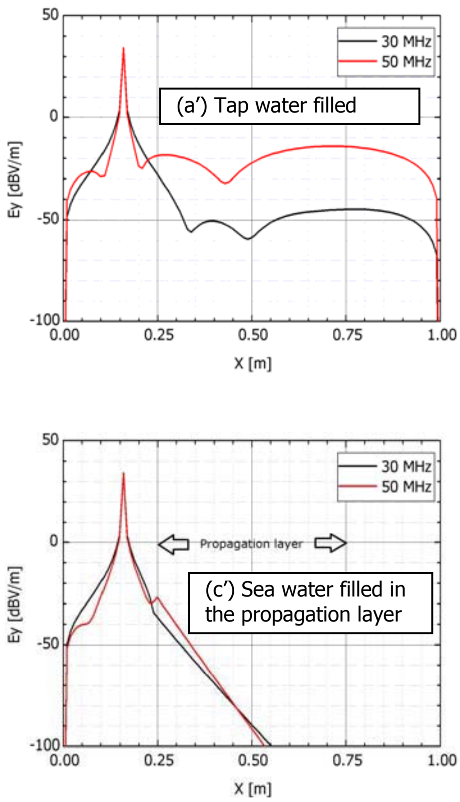

Figure 11. Electric field distributions along the x axis were simulated in the both types. (a') The buffer and propagation layers are filled with the tap water only. (c') The propagation layer is filled with the sea water.

We should establish a model describing this new fact which is already shown by the team of Lucas [8], but we must verify our experimental data using a rigorous apparatus, before that. In order to understand the fact, a microscopic treatment of dielectrics in the Maxwell's equation would be necessary if the result is true.

III. Concluding Remarks

We carried out three types of the HF wave propagation experiments: the test near the pier in JAMSEC, the sea trial in the open sea, and the laboratory test using the Faraday cage. We may find a valuable possibility in the utilization of underwater HF wave as a high-speed and mid-range communication. We need to perform more precise experiments and the theoretical considerations of the underwater HF wave propagation for achieving our target.

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