Electromagnetic Under-the-Ice Localization and Communication

Hiroshi Yoshida
Institute of Arctic Climate and Environment Research(IACE)
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Yokosuka, Japan
yoshidah@jamstec.go.jp

Tatsuro Yonekura
Faculty of Science and Engineering
Iwate University
Morioka, Japan

Masaharu Takahashi
Research Center for Frontier Medical Engineering
Chiba University
Chiba, Japan

Nozomu Ishii
Institute of Science and Technology
Niigata University
Niigata, Japan

Qiang Chen
Department of Communications Engineering
Tohoku University
Sendai, Japan

Ryotaro Suga
Wireless Networks Research Center
National Institute of Information and Communications Technology (NICT)
Yokosuka, Japan

OCEANS 2022, Hampton Roads | 978-1-6654-6809-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/OCEANS47191.2022.9977045

***Abstract*—This paper proposes a localization method for underwater vehicles operating below sea ice and describe experimental research results comprising the basis of the method. The method integrates a hybrid navigation system of Doppler velocity log (DVL) - inertial navigation system (INS) and an under-the-ice electromagnetic localization (UEML) system. If ice-relative dead reckoning would achieve positioning error comparable to bottom-relative one, the hybrid system has position error of a few meters for a kilometer. An underwater part of the UEML system installed on an underwater robot transmits EM beacon. A part in air of The UEML system on which is set a drone above or a vehicle on ice surface measures its absolute position with a GNSS (Global Navigation Satellite System) and EM field strength. It thus makes a 2D-EM field map as an absolute reference for underwater robot. We carried out experimental research of EM propagation among air, sea ice, and seawater. It is recognized that attenuation of EM wave of 10 kHz between seawater and ice-surface (in air) vertically is about 80 dB at depth of 5 m when a 1 m-class-small loop antenna and an underwater 2 m-half sheath antenna are used. We estimated that vertical coverage of the UEML is 17 m assuming a link budget of 134 dB from measured data with fitting curve calculated by Sommerfeld equation. In contrast, at distance between the antennas of 80 m, decay becomes 134 dB when depth of the 2 m-HSA is 4 m due to lateral waves. From these results, beacon signal will be received in relatively wide area in air when an underwater robot approaches to less than 17 m. The communication test in horizontally shows that service range of PSK modulated waves of 1 kbps is over 40 m. From these results we can estimate that communication between the drone and the underwater robot can be also established in depth of less than 17 m. In this depth range we can perform position update of the navigation system installed in the robot. This limitation would not be crucial problem since one of purpose of under-the-ice robot is observation of and survey near the ice bottom. If deep sea survey is required, taking two underwater vehicles configuration may be better.**

***Keywords*—Underwater electromagnetics, under the ice, localization, communication, AUVs, the Arctic**

I. Introduction

Research and monitoring under the ice in polar region are an important issue to understand danger posed by global warming and ocean acidification [1-3]. Autonomous underwater vehicles (AUVs) are a promising platform which carries sensors to and performs observation under the ice. Observation data must include the location where the data is measured. But it is not easy to deploy an underwater localization system from the ice surface. In open sea an acoustical super short baseline (SSBL) or Ultra SBL (USBL) system installed on a vessel, or a boat is widely utilized. In ice-covered sea a localization system must deploy from the ice surface because the ice prevents the entry of vessels. A survey team needs much effort and cost to dig a hole on the ice if they deploy SSBL systems since acoustic waves does not propagate in the ice. In 2010, an Explorer AUV built for Natural Resources Canada by International Submarine Engineering was deployed to Arctic and successfully completed under ice bathymetric surveys covering distance of about 1000 km [4]. In the experiment an original acoustic long-range homing system which has service rang of 30 km and a short-range localization system developed were deployment from ice-holes.

We propose an under-the-ice electromagnetic localization (UEML) system for underwater robots or AUVs to achieve an easy and low cost deployment. First, we introduce basics of the UEML system and an idea of AUV operation. The third section is main section of the paper. In the section, Basic of EM propagation in seawater, test equipment, propagation test, and communication test are described. Finally, we show a prototype of the EM system designed with obtained knowledge and describe a test plan.

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

978-1-6654-6809-1/22/$31.00 ©2022 IEEE

II. THE UEML SYSYTEM

Attenuation of EM wave energy at 10 kHz is theoretically calculated as 3.5 dB/m in seawater of $\sigma \sim 4$ S/m. If an EM system has dynamic range of 100 dB, service range of the system becomes about 30 m since energy dumping in air and sea ice is much smaller than that in seawater. This means that a robot should approache bottom of the ice less than 30 m if we use EM wave for localization and/or communication between a base station in air and the underwater robot. After passing through seawater layer, EM propagation loss in air is drastically reduced. Diffusional decay in air at 10 kHz is estimated by plane wave approximation as 12 dB at distance of 10 km from the EM source. For example, a receiver of the base station at 10 km distant from the AUV diving point can receive EM signal transmitted from the underwater source, when the source is located under the ice at depth of about 25 m

To utilize the UEML system to an underwater robot, the robot must have a DVL-INS hybrid navigation system. The UEML system enables the navigation system to minimize position error accumulated during long cruising. High-class hybrid system typically has position error of a few meters per km if bottom tracking is available. In the ice-covered area one can use ice bottom tracking but moving ice makes large position error. From above discussion, position update of the navigation system with the UEML needs every 10 km or less because underwater service range of the UEML system is 30 m and a robot typically makes position error of 20 - 30 m during 10 km cruising. Air drone is suitable platform as a base station since it flights over 10 km. A drone powered by gasoline is more suitable considering flight distance and weight of the UEML system. A remote-controlled snow vehicle is an alternative platform when ice-surface condition is good.

The UEML system consists of two major components: a robot locator and an EM transceiver as shown in Fig. 1. The robot locator consists of an underwater beacon and an EM strength mapping unit. The mapping unit estimates absolute coordinate value of the beacon in horizontal plane from a 2D-map created by using a GNSS and EM strength meter. The EM transceiver mainly informs the coordination estimated to a navigation system of an underwater robot. The beacon and a receiver of the transceiver are installed in an under-the-ice robot. The mapping unit and a transmitter of the transceiver are mounted on a drone or a vehicle in air.

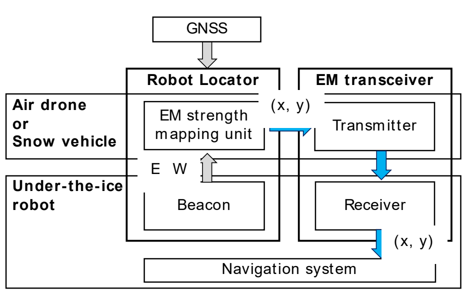

Fig. 1. System configuration of the UEML system.

Figure 2 shows an example of operation of the UEML system. On time preprogrammed an AUV approaches to ice bottom and its beacon then transmits EM carrier wave. At the same time, a drone takes off and explores the carrier wave. Once the drone detects the wave, it goes toward the point over the AUV using gradient of the EM field. The AUV keeps its position near the ice bottom until it receives the position information. The drone makes 2-D EM map by lawn mower (zigzag) flight and estimates the 2D-position of the AUV. The drone lands on or approaches ice surface, communicating with the AUV to send the position information. The AUV automatically updates the position of the navigation system, restarting the cruising.

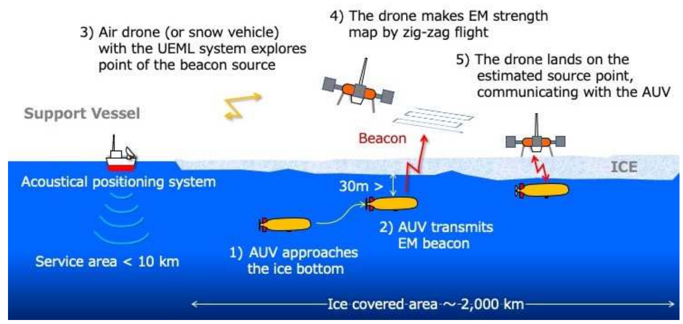

Fig. 2. An operation example of the localization with the proposed method.

III. PROPAGATION BETWEEN ICE SURFACE AND SEAWATER

A. *Why we need underwater EM propagation measurement*

It is generally considered that usage of electromagnetic wave is not available in seawater. It is true if your EM items are smart phone, TV, radio etc. of which frequency band is around microwaves. On the other hand, low frequency (LF) band is used in submarine communication. In frequency range below several hundred MHz, seawater is treated as a conductive material, thus $\sigma_{sea} / \omega\varepsilon >> 1$. σ_{sea} denotes conductivity of seawater (~ 4) , ω is angular frequency, and ε is permittivity. From transmission equation, attenuation in seawater is calculated to be about 3.5 dB per meter. But real seawater would be more complicated material for electromagnetic field including near field effect. There are very little literatures related to EM propagation among air, sea ice, and seawater. We thus need to perform experimental study of underwater, under ice, and air to sweater propagation to make a decision about effectiveness of the proposed method.

B. *Test equipment*

To measure the LF propagation we developed and tested several types of small antennas including underwater antennas: small loop antennas (SLA), inductive loaded dipole antennas (LDP), underwater half sheath antennas (HAS) [5], underwater ferrite core antennas (FCA), and underwater small loop antennas (USLA). We finally chose SLA and HSA for measurements by prior tests. Fig. 3 shows the SLA for a transmitter to be set on ice surface and the HAS for an underwater receiver. Outer dimension of the SLA is 970 mm x 330 mm x 60 mm. Two antenna elements were assembled for center frequency of 10 kHz and 100 kHz, respectively. The SLA for 10 kHz consists of a multi-turn loop made from cupper Litz wire, plastic capacitors for resonance and a matching loop. It for 100 kHz, single loop antenna made from cupper plate of 50 mm width, 0.5 mm thickness. Band width ratios (BWR) of the SLAs are 1 % or less at impedance matching point in air. The HSA is a combination antenna of an electrode and a pure water insulated dipole antenna. Long element HSAs and short element HSAs are made. They consist of two elements made from brass rods (ϕ5 x 1000 mm x 2 and ϕ5 x 350 mm x 2), PVC pipes (ϕ60 mm x 1000 mm and ϕ60 mm x 350 mm) filled in pure water, and matching circuits. VSWR and BWR of both of long and short HSAs in seawater are about 2 and over 100 %, respectively.

A transmitter was composed of a function generator and a 40 dB power amplifier. A real-time spectrum analyzer was used as a receiver. A network analyzer measured impedance matching of each antenna. Output power was supplied to a TX antennas via a 30 m coaxial cable (5D-2V). An RX antenna and the receiver is connected to a 30 m long 5D-2V cable. A set of an electric field strength meter and a standard loop antenna was set near the transmission antenna to monitor electric field strength for not exceeding the maximum radiation field strength regulated. A CTD (conductivity-temperature-depth) meter measured vertical depth profile of conductivity and temperature of seawater.

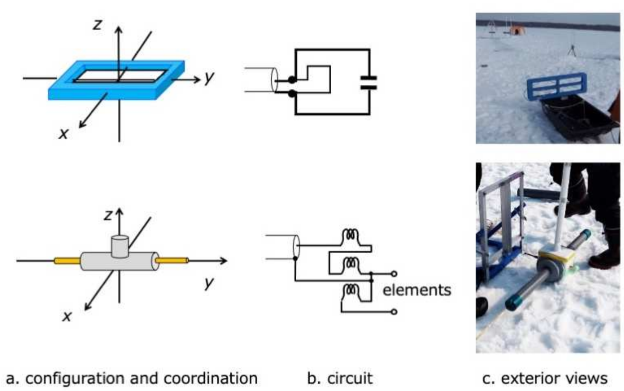

Fig. 3. Antennas developed for the experiments. Upper: SLA and Lower: HSA. Upper right picture shows the SLA on a sled. Lower right picture shows the 2 m HSA with a 5 m FRP rod.

C. Propagation tests

We intended to evaluate horizontal propagation near ice surface and vertical coverage of LF wave in a real site with air-ice-seawater layer. These tests have been carried out in Saroma Lake, Hokkaido, Japan in every winter since 2018. This lake is a brackish-water and frozen lake. We had chosen almost the same point with water depth and ice thickness were 4 ~ 7 meters and 45 ~ 60 cm, respectively.

Figure 4 shows the experimental setup for measurements of horizontal propagation. The RX antenna was deployed into seawater at 2 m or 4 m depth through an ice hole drilled. The x-axis (in Fig 3 a) of the HSA was steered toward the TX antenna. The SLA was set on a sled and moved on ice-surface which covered with a small amount of snow. Antenna polarization of the SLA is shown in Fig. 5. Measured distance between the RX and the TX was from 1 m to 100 m. TX frequency was 10 kHz and 100 kHz.

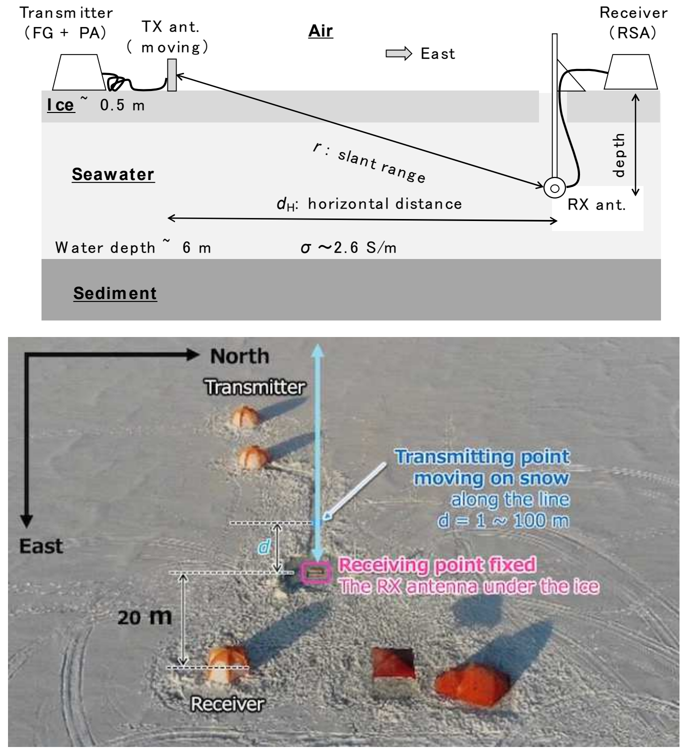

Fig. 4. Experimental configuration for horizontal propagation measurements in Saroma lake. Upper: cross-section view and lower: a snap shot of the test site in 2020.

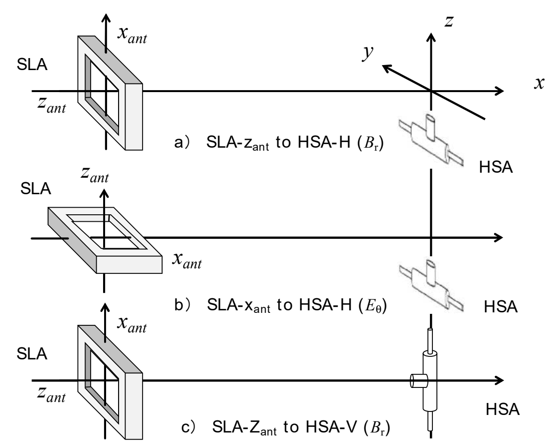

Fig. 5. Antenna polarization.

A typical obtained propagation characteristics of ice-surface to seawater in frequency of 10 kHz is shown in Fig. 6. Open circle and closed circle with solid line denote field components of B_r and E_θ, respectively when the HSA is aligned along y axis. Closed circle with dotted line denotes B_r when the HSA is aligned along z axis. Conductivity of seawater measured was 2.6 S/m. From Fig. 6, we recognize that when the HSA is laid on horizontal plane, we can get more better signal strength. LF propagation measured horizontally in 100 kHz is shown in Fig. 7. In this test we did not measure that in the case of the vertical HSA setting. We decided that 100 kHz LF wave will be not used in the system because data show rapid decays of signal strength.

Solid gray and black lines in Fig. 8 show fittings of simulation results calculated with Sommerfeld integral solution in the case of the HSAs laying on horizontal plane. The plots calculated are normalized at 4 m. The curve measured in combination of SLA-x_{ant} – HSA-H and SLA-z_{ant} – HSA-H are fitted with E_θ and B_r component, respectively. Discussion below is interesting, but it gets off the subject. This would represent that the dominant component of EM waves in seawater is not magnetic field but rather electric field which converted to conductive current. This fact is coincident with the fact that the HSA, which drives conductive current, has good performance in seawater.

By using the data obtained and calculated we can estimate horizontal coverage of the UEML system. If output power of a transmitter and sensitivity of a receiver are assumed to 10 Watts (+40 dBm) and -100 dBm, the system dynamic range becomes 140 dB. It means attenuation of 140 dB is capable. As a result, maximum horizontal service range is estimated as radius of 100 m. Actual service range depends on yaw angle of the TX and RX antenna. Therefore, the TX and RX antennas should be omni directional in horizontal plane, practically.

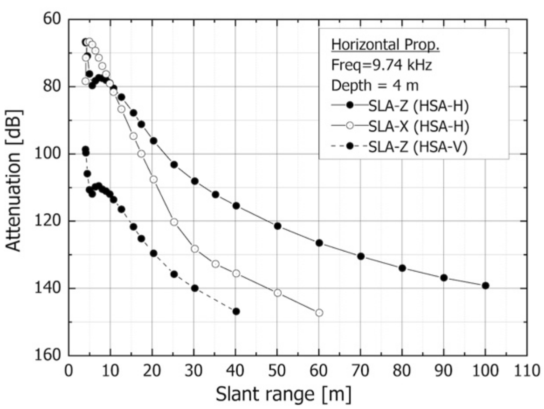

Fig. 6. Attenuation measured between air, sea-ice, and seawater in Saroma lake at frequency of 10 kHz.

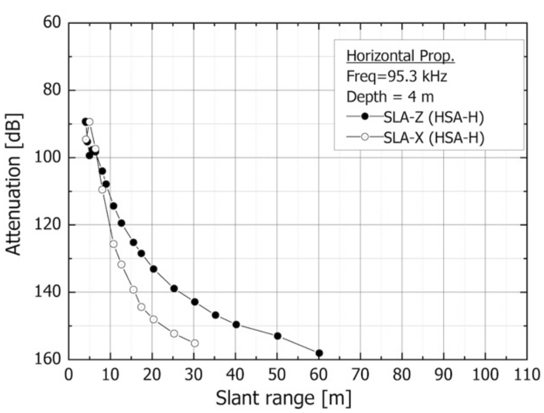

Fig. 7. Attenuation measured between air, sea-ice, and seawater in Saroma lake at frequency of 100 kHz.

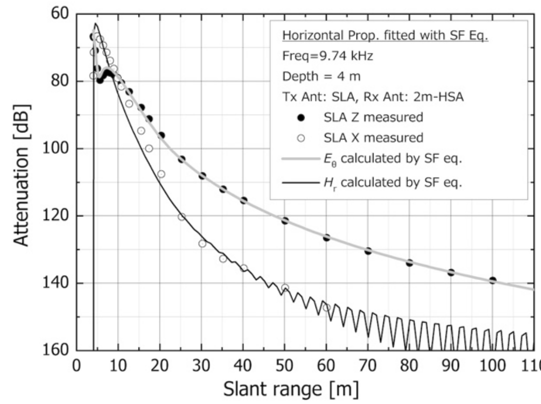

Fig. 8. Low frequency attenuation measured between air, sea-ice, and seawater in Saroma lake.at 10 kHz.

Figure 9 shows vertical propagations when 10 kHz EM waves penetrate boundaries among air, ice, and seawater. Receiving antenna was the SLA at the coordination of (x = - 0.5 m, y = 0 m, z = + 1 m). The aperture plane of the SLA was laid on x-y plane above the ice surface. The HSAs were deployed with a plastic pole at (0 m, 0 m, depth) where depth is measured from the ice bottom. Ice thickness was about 0.5 m. Closed circle and open circle denote attenuations obtained with transmitting antennas of the 2 m-HSA and the 70 cm-HSA, respectively when σ = 2.6 S/m. Cross denotes of the 70 cm-HSA when σ = 2.4 S/m. Black and gray liens denote y-component of electric field, E_y and z-component of magnetic field, B_z calculated, respectively. We estimate vertical coverage of the UEML system in same as above. Because the system allows attenuation of 140 dB, maximum vertical service range becomes 18 m. Actual service range would depend on antenna orientation and environmental noise. In vertical propagation, coverage is shortened five times than that in horizontal propagation because path of lateral wave [6] does not exist vertically.

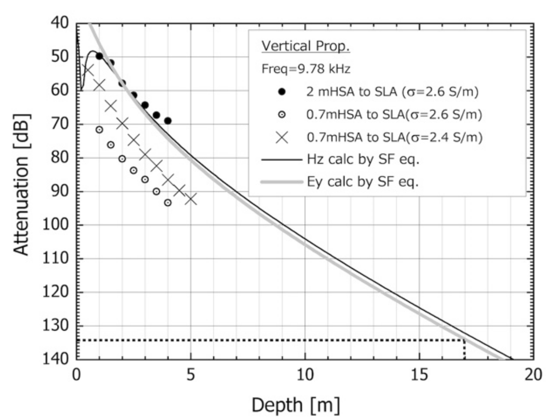

Fig. 9. An air-ice-sea boundary propagation in vertical at 10 kHz.

D. Communication Test

A functional model of the UEML for communication test consists of major three parts: a control console, a transmitter part

(TX) on the ice surface, and an underwater receiver part (RX) as show in Fig 10. The control console commands test functions to the TX and the RX. It has modulation and demodulation functions of each of software defined radios (SDRs) as well as measured data logging function. The TX consists of an SDR, a power amplifier a CPU board, a GPS, and a small loop antenna. The RX consists of an SDR, a pre-amplifier, a CTD meter, an inertial measurement unit (IMU) with a magnetic compass for measuring attitude of the RX in seawater, a battery unit, and a 2 m-half sheath antenna. The console communicates with the TX via a Wi-Fi or an ethernet cable, and with the RX via an optical fiber cable. Electric units of the RX are installed in a main pressure hull except the HSA, the CTD, the IMU, and the battery. An exterior view of the RX is figured in Fig. 11.

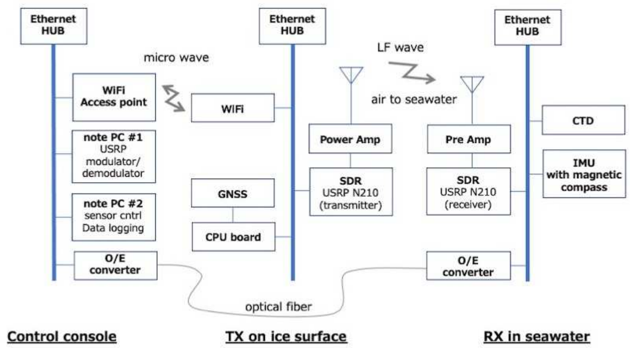

Fig. 10. Function blockdiagram of the function model for communication test

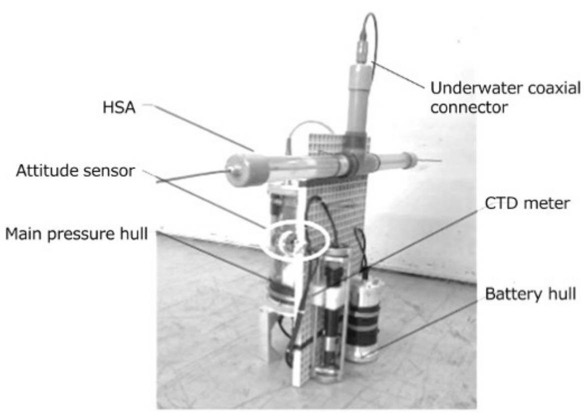

Fig. 11. An extorior view of the underwater receiver unit (RX). The 2 m-HSA is mounted on the top side of the frame. Its hight is about 0.7 m and weight is about 20 kgs.

Fig. 12 is illustrated the setup of the field tests. The RX was deployed in seawater with a hand winch at depth of 2 m. We measured bit error rate (BER) of communication between the TX and the RX. Horizontal distance measured was changed by moving the SLA on a sled. Modulations in the test were PSK, ASK, and FSK. The data structure used consists of 32 bits preamble and 512 bits random data. Data speed is 1 kbps. Error correction is not used. Tested frequency were 10 kHz and 100 kHz. Table 1 lists obtained service ranges defined as the distance where BER measured becomes 0.01 or above, and values in parenthesis denote signal to noise ratio (SNR) at the distances. The reason that data of ASK at 10 kHz is not obtained would be signal distortion caused by 1 % bandwidth ratio of the SLA. In a prior test in our laboratory, required SNRs of PSK and FSK at 10 kHz were obtained as 12 dB and 18 dB, respectively. In the field test, higher SNRs were needed. This would be the same reason as above. We tried to reduce transmission speed to 100 bps, but BER was degraded. Reducing of transmission speed results in ten times longer transmission time. External fluctuations and noises would affect to the long data train and then make data errors. In a prototype design, low transmission rate and short data size will be needed.

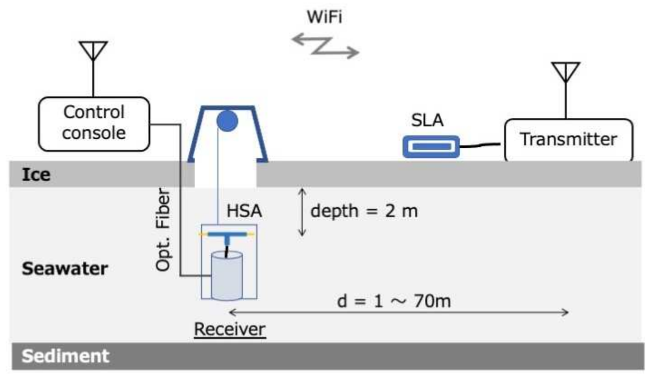

Fig. 12. Field set up of communication tests.

TABLE I. SERVICE RANGE IN BER $\geqq 10^{-2}$

Frequency	Distance [m] (SNR [dB])		
	PSK	***FSK***	***ASK***
10 kHz	40 (25)	30 (30)	-
100 kHz	20 (25)	15 m (30)	15 m (30)

In order to design a 10 kHz UEML prototype to be installed on an underwater robot, a wireless link is designed below. We assume that PSK of error-free SNR = 12 dB which corresponds to received power of about -97 dBm in the measurement system. Allowable link budget becomes 134 dB with a 3 dB margin if we set transmission power of +40 dBm. From the vertical attenuation measured with the fitting curve, maximum coverage is estimated as 17 m (see dotted line in Fig. 9). In practical case, we must consider polarization and orientation of antennas, external noises and change of conductivity of seawater. Problems of antenna polarization and directivity will be solved because new cross HSAs have been developing. A 3 dB loss is thus considered to the budget as antenna system loss tentatively. Conductivity of Saroma Lake is about 2.6 S/m. Similar conductivity can be found in the Arctic Ocean. However, there are locations where the conductivity exceeds 4 S/m. Difference of attenuation per unit between conductivity of 4 S/m and 2.6 S/m is 0.67 dB/m. As a noise margin, we subtract 3 dB from the link budget. On the other hand, error corrections and a signal processing would gain about 6 dB to the budget. Totally the loss of link budget is just the loss by change of conductivity. This loss results in reduce of cover distance to about 10 m. The underwater robot equipped with a transceiver of the UEML should be close vertically to the ice-bottom at least 10 m to establish communication with a robot on ice-surface or in air. This requirement would be not crucial problem since one of purpose of under-the-ice robot is observation of and survey near the ice bottom. If a deep-sea survey under-the-ice is required, one solution would be to prepare two underwater robots. One is equipped with the UEML and an acoustic communication/ localization system for cruising near ice bottom. The other is a deep-sea robot equipped with an acoustic communication system and a transponder.

IV. The UEML System Prototype Under Development

We have designed and assembled a prototype of an UEML system mounted on a remotely operated vehicle (ROV) and a crawler robot based on the obtained data and above discussion since 2021. An underwater part is made up of a small ROV equipped with a beacon, two 70 cm-HSAs, a CTD meter, an IMU, and two pressure hulls including a receiver, an optical communication system, a battery, and so on as pictured in Fig. 13. We have developed a crawler robot which is a snow vehicle since 2019. The EM strength mapping unit and the transmitter, which are installed in watertight cases for each, two SLAs for 10 kHz, and a battery are mounted on the crawler robot as pictured in Fig. 14. The robot is still under development but was tested several times in snow area including Saroma Lake. Fig. 14 shows how to make a field strength map using the crawler robot. Maps will be made with EM strength and horizontal position measured by zigzag cruising in area of about 10 m x 10 m with interval of about 1 m. We can find a maximum or null signal point where indicates point of the beacon from the map. We estimate position error by above method to a few meters from results of an EM simulation and a field test.

In near future, we improve the prototype and carry out tests in Saroma Lake or other ice-covered seawater site. The detail of the prototype will be given in reports of the test results.

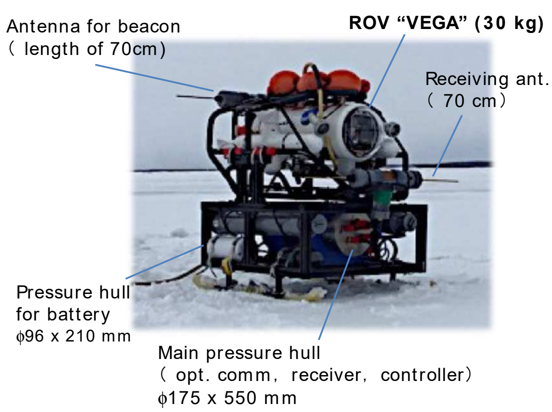

Fig. 13. The ROV equipped with the beacon, the antennas, and the pressure hulls.

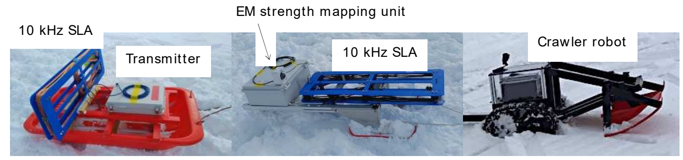

Fig. 14. The crawler robot towed the mapping unit (center) and the transmitter.

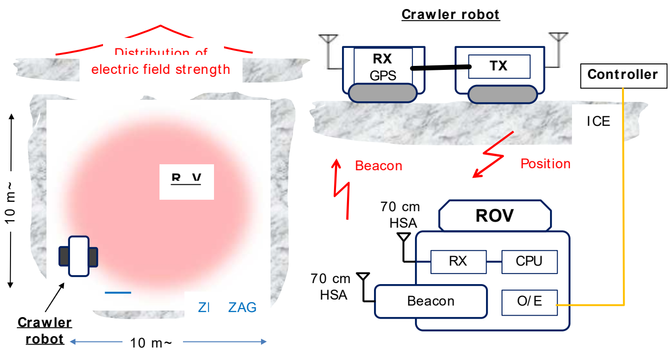

Fig. 15. An idea how to make a field strength map by the crawler robot and how to find a position of the underwater robot.

Acknowledgment

We would like to thank Mr. Oiwake, Mr. Sato, and Mr. Noisshiki from Japan Radio Co. Ltd., for developing software of the SDRs and supporting field tests.

References

[1] J. E. Walsh, J. E. Overland, P. Y. Groisman, and B. Rudolf, "Ongoing climate change in the Arctic," AMBIO, vol. 40, pp. 6-16, December 2011.

[2] E. A. Barnes, "Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes," Geophys. Res. Lett., vol. 40, pp. 4734-4739, September 2013.

[3] Harui, W. Evans, J. N. Cross and R. A. Feely, "Ocean acidification risk assessment for Alaska's fisheries sector," Prog. Oceanogr., vol. 126, pp. 71-91, August 2015.

[4] Chris Kaminski, Tristan Crees, James Ferguson, Alexander Forrest, Jeff Williams, David Hopkin, Garry Heard, "12 Days Under Ice - An Historic AUV Deployment in the Canadian High Arctic," Proc. Of IEEE/OES Autonomous Underwater Vehicles (2010).

[5] Hiroyasu Sato, Naomichi Fujii, Qiang Chen, Nozomu Ishii, Masaharu Takahashi, Ryotaro Suga, Koichi Uesaka and Hiroshi Yoshida, "Dipole antenna with sheathed-cover for seawater use," Proc. ISAP 2017, POS1, 1376, Phuket, Thailand, Oct. 2017..

[6] R. W. P. King, Lateral Electromagnetic Waves, Springer-Verlag, New York, 1992.