Underwater Robot Navigation Under Sea Ice Using Very Low Frequency Electromagnetic Waves in The Polar Regions

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***Abstract* - We propose a method using electromagnetic waves in the VLF band as a positioning system under sea ice, which is an issue for AUVs, which are expected to serve as a platform for surveying under sea ice in polar regions with knowledge gaps for climate change research. In order to establish this system, it is necessary to clarify the characteristics of radio wave propagation in the polar sea ice area. Our team conducted radio propagation measurements in the sea ice in Alaska in May 2024, and was convinced that the proposed method is feasible in principle in the polar regions.**

***Keywords* — VLF, Polar regions, AUV, Navigation, Under-ice.**

I. INTRODUCTION

Climate change caused by greenhouse gases is progressing rapidly, and the average global temperature in 2024 was 1.5°C above the pre-industrial level. Warming in polar regions such as the Arctic and Antarctica has a significant impact on mid-latitude climate by causing stratospheric polar vortex disruption [1]. In the Arctic, the inflow of solar heat energy due to the lowering of the albedo is warming the seawater, and the inflow of warm seawater from the Pacific and Atlantic Oceans is warming the water several tens of meters below the surface. Although the polar ice is melting, much of the region is still covered with ice, and only limited observations are available, leaving a knowledge gap in the region. However, detailed observations under sea ice are essential to correctly understand the mechanism and status of rapid sea ice and ice sheet melting, and to take countermeasures against climate change.

Autonomous Underwater Vehicle (AUV) is a very effective underwater robot for unmanned, low-cost investigation of large areas under the sea. Because Global Navigation Satellite System is not available underwater, a hybrid of three positioning methods (inertial navigation system: INS, Doppler velocity log, and acoustic positioning) is usually used. Acoustic positioning systems require a reference station (usually a mother ship) and are difficult to use in ice-covered sea areas.

In this paper, we describe the results of measurements of vertical VLF radio propagation characteristics and electromagnetic field distribution on the sea ice surface for positioning in the Arctic Ocean, which our group has been studying since 2016 [2].

II. SYSTEM DESIGN

The AUV, a test bed for VLF navigation, is equipped with a sonar and a camera for imaging sea ice bottom and navigates several meters to several tens of meters below the sea ice. The AUV is equipped with a CTD (Conductivity, water temperature, and depth) meter, a fluorescent turbidity meter, and a sampler to sample organisms in the sea water. Figure 1 shows an overview of the AUV to be used in the design of the new navigation system proposed.

<u>Specifications of the AUV “COMAI”</u>
Dimension: 2.3 (L) x 0.6 (W) x 0.7 (H) m
Weight: 330 kgs in air
Cruising range: 30 km max.

Fig. 1. The VLF navigation test bed.

The AUV is equipped with a VLF beacon and transmits the beacon signal under the sea ice, and the beacon signal is detected on the ice. The current navigation problem is that the AUV cannot know where it is under the sea ice (neither the AUV itself nor the operator). Therefore, rather than constantly measuring the exact position, the VLF positioning method periodically updates the AUV's position with an absolute error of a few meters. The goal is to greatly reduce the risk of AUVs being lost under sea ice, and to compensate for the error accumulated in relative position measurements through periodic updates.

Fig. 2 shows the positioning procedure. The AUV will navigate at depths of 3 to 50 m, and the AUV's existing onboard positioning system will be used for short-term positioning. For operations in the Arctic Ocean, assuming an error of 1 km per hour and a position correction once every 30 minutes, the AUV will never completely lose its position.

The AUV location is determined by estimating the wave source location using an electric field map. When the frequency is set to 10 kHz, the attenuation is about 3 dB/m in typical underwater conditions, so the underwater positioning service area can be estimated to be a maximum of 30 meters. If the AUV moves at high speed during the search, it will not be able to locate the position. Therefore, the positioning conditions are set as follows: (1) AUV depth is set to 3 to 6 m below the ice, and (2) AUV speed is set to 0.5 kt. Assuming an air drone speed of 10 m/s, it takes less than 2 minutes to travel to the vicinity of the AUV, and 30 s/area when using lawn mowing navigation (20 m^2 with 2 m side line spacing) to search for wave source location estimation, during which the AUV moves about 8 m. Therefore, the position and displacement at a certain instant are estimated from the displacement of the electric field map by multiple scans. The measured values are transmitted from the air drone to the AUV via electromagnetic communication, and the AUV's horizontal position is updated accordingly. The vertical position is measured by the AUV's onboard depth meter and is therefore unnecessary.

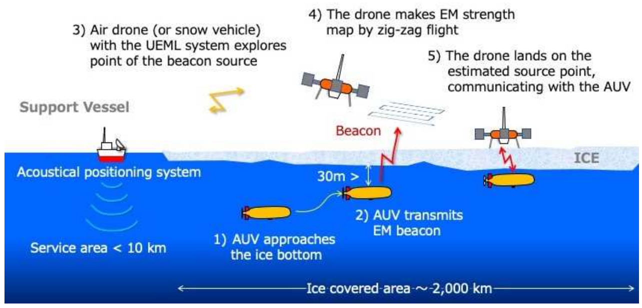

Fig. 2. VLF Navigation Procedure.

III. Measurements in the Arctic Sea Ice Area

VLF electromagnetic wave propagation measurements in the Arctic Ocean and electric field map measurements were carried out on sea ice off Utqiagivik, Alaska, in May 2024. The sea ice thickness was 1.2 m, the seawater temperature was about -3°C, and the conductivity of the seawater was 4.8 S/m. The main measurement equipment included a 70 cm-half-sheath antenna (HSA) and a small-loop antenna for underwater use [2], a handmade underwater transmitter housed in a pressure-hull, and an underwater drone (Max II Pro, Chasing).

In the three-layer vertical radio propagation measurement of sea water - sea ice - ice, an underwater drone equipped with the HSA and the transmitter was placed in the sea, and a small loop antenna was placed 30 cm away from the sea ice surface. The maximum values were recorded at different depths when the underwater drone was cruised. For the electric field map on sea ice, the electric field distribution on the sea ice surface was measured on a 10 m x 10 m mesh by the small-loop antenna while the half-sheath antenna for transmission was fixed at a depth of 3 m in the sea. The results are shown in Figures 3 (a) and (b), respectively. Fig. 3 (a) also shows the propagation characteristics measured in the open sea (red circles). It can be confirmed that the difference between the sea ice area and the open sea is only the thickness of the ice.

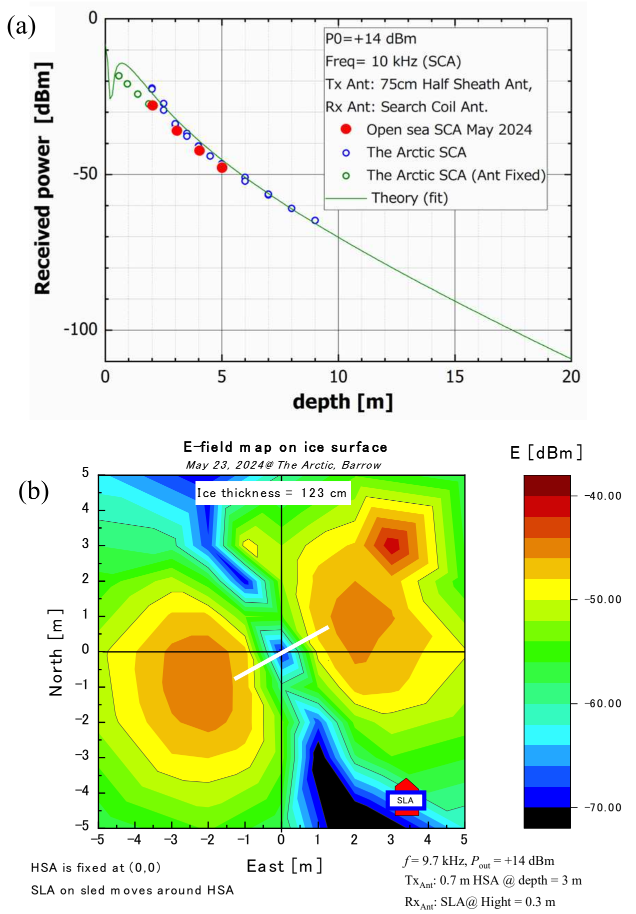

Fig. 3. VLF propagation in the Arctic measured. (a) Vertical propagation, (b) electric field distribution on the ice surface.

The measurement results in the Arctic Ocean show that the VLF radio wave propagation characteristics in the three-layer structure of seawater, sea ice, and air are almost the same as those in the open sea if the sea ice is thin and the conductivity is the same. At present, the service area for positioning and communication applications in the vertical direction of seawater with a conductivity of about 5 S/m can be estimated to be within 20 m for a half-sheath antenna size of 70 cm class. The obtained electric field map indicates that the k-map may be used to estimate the position of the AUV if the distance to the AUV is close enough. In the presentation, these details will be reported.

REFERENCES

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