Development of Underwater Short-Range Sensor Using Electromagnetic Wave Attenuation

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***Abstract*—In this paper, we discuss a novel underwater short-range sensor using electromagnetic (EM) wave attenuation. We use the revised Friis–Shelkunoff formula to calculate the EM wave attenuation underwater as a function of distance. This requires knowledge of the antenna gain underwater, which is very different from the gain in air, and also the attenuation constant which depends on the water conductivity. We calibrated the gain and attenuation in a ranging experiment and also in a 2-D localization experiment. Both methods agreed, confirming that *in situ* calibration of a 2-D localization experiment is feasible. The localization results show good accuracy, validating the sensor model and showing that multipath effects can be made negligible in such an experiment.**

***Index Terms*—Underwater localization, underwater distance sensor, electromagnetic wave, received signal strength(RSS).**

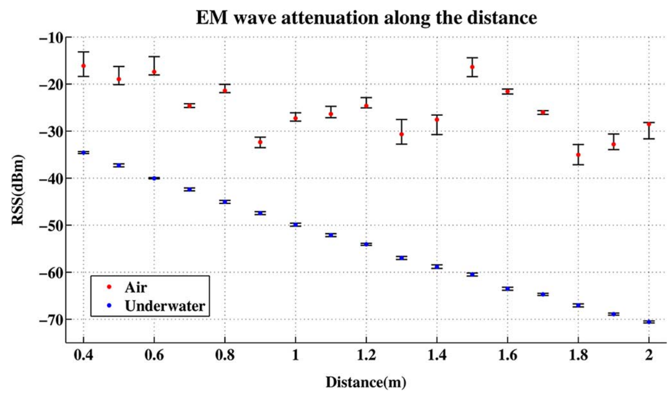

Fig. 1. Plot of the RSS according to the distance: The red dots and error bars show the RSS value and variation in the air, and the blue dots and error bars show the RSS value and variation in tap water at the same power and frequency (10 mW with 420 MHz and Helix antenna, respectively).

I. Introduction

RECENTLY, underwater environments have been the focus of both academic and military fields. The importance of natural resources buried underwater is increasing owing to depletion of ground resources. To develop and localize these resources, operate underwater vehicles such as submarines and unmanned underwater vehicles (UUVs), and construct an underwater sensor network [1], an accurate localization method using underwater sensors is required. However, it is difficult to utilize conventional optical above-water sensors in an underwater environment owing to characteristics such as backscatter, absorption, and poor visibility. For these reasons, acoustic sensors are utilized for their low attenuation and reliable underwater operation in many applications [2]–[5]. However, acoustic sensors do not guarantee a range estimation performance in a dynamic object due to the speed of sound, and also in complicated structure environments due to the multipath effect and diffraction scattering. Furthermore, the cost of an acoustic sensor is relatively high, and it also contributes to noise pollution in the underwater environment. Therefore, an alternative sensor to use in complex underwater environment is needed [6]–[9].

To overcome these shortcomings, a localization method based on the received signal strength (RSS) of an electromagnetic (EM) wave is suggested for an underwater environment. There have been numerous attempts to use EM waves and their signal strengths in air for distance measurement and localization purposes [10]. However, because of the low attenuation by the medium, EM wave localization in air is easily affected by multipath signal propagation and cancellation, which makes accurate distance determination difficult. To illustrate this we show two received signal tests using the same equipment in Fig. 1, one in air (marked with red dots) and the other underwater (marked with blue dots). The underwater test will be discussed in detail in Section IV. Here the important point is that the underwater test shows a very smooth range dependence whereas the test in air shows a very erratic range dependence [11].

It is more difficult to calculate the received signal strength underwater than in air. Not only is the signal attenuated by the complex propagation constant, but also there is significant loss in coupling the antenna to the underwater medium and this loss depends on the nature of the antenna [12]. Fortunately the coupling loss is simply a constant and the propagation constant can be calculated quite accurately from the conductivity of the water. In this work, we have first verified the underwater Friis–Shelkunoff formula [13] with a ranging experiment. In applying this to a 2-D localization system, we have calibrated the

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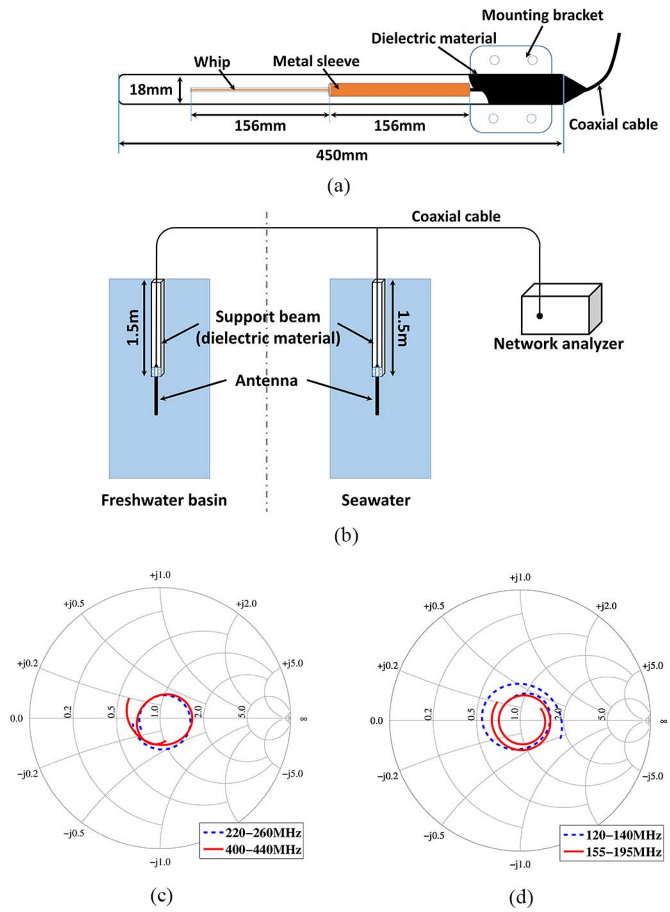


Fig. 2. (a) The manufactured half-wavelength sleeve-dipole antenna. This antenna has a 3-dBi directional pattern, and it is covered by a dielectric material. The antenna is sealed between antenna and cable for waterproofness, and uses coaxial cable to prevent signal leakage. (b) The experimental setup for antenna input impedance measurement in underwater condition. The antenna is connected to a dielectric material to maintain a 1.5-m depth during the experiment. (c) and (d) The Smith charts of input impedances at fresh water and seawater using each antenna. The input impedance is measured using Agilent Technologies network analyzer (N5230A).

antenna gain and propagation constant from measurements between the anchor nodes of the localization system. This allows us to recalibrate every time the localization system is used.

This paper is organized as follows. Section II describes the related works about previous localization methods using EM wave attenuation. Then, we introduce our approach to solve the previously mentioned problems in Section III. We describe the experimental test bed setup and the procedure for range measurement and 2-D localization to verify the new sensor model and calibration method in Section IV. Section V describes the field test to check the feasibility of the sensor in a shallow seawater environment. Finally, we discuss our research and future work in Section VI.

II. Related Works

A sensor using an EM wave can be divided according to the environment. For air conditions, researchers suggest many approaches for using EM wave in localization. Most outdoor localizations use global positioning systems (GPSs) with the time-of-arrival (TOA) method. However, positioning in an indoor environment uses the RSS or a received signal strength indication (RSSI) range sensor owing to the increasing uncertainty of GPS in an indoor environment. However, the RSS is significantly affected by not only the distance but also by surrounding environmental effects. Thus, many studies have demonstrated localization using an RSS range sensor with a stochastic approach rather than a deterministic approach [14], [15]. Another approach is a fingerprint method such as a radio map, which memorizes the information about the RSS according to the position and applies actual localization using pattern matching [16], [17].

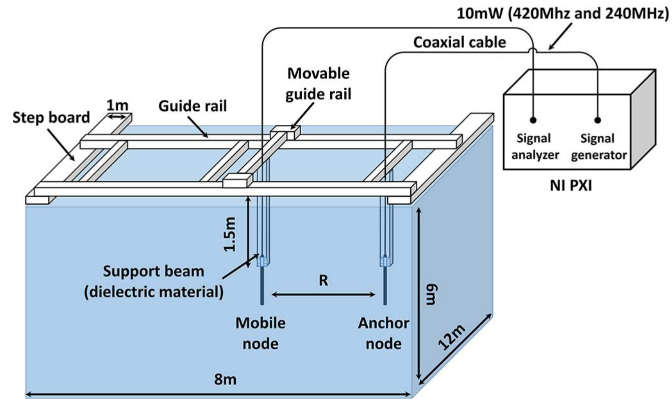


Fig. 3. Experimental environment for validation of the distance sensor model. An aluminum guide rail is installed for alignment between the antennas and precise distance measurement. Dielectric support beam is used to prevent the multipath propagation effect.

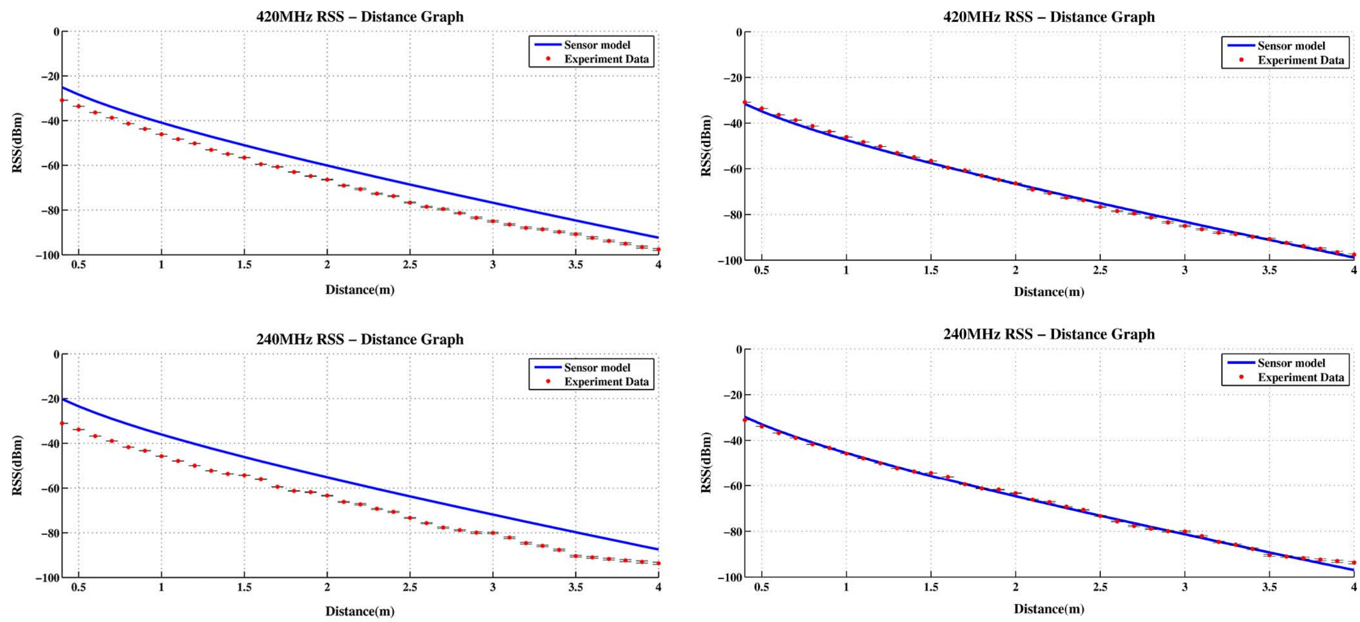
On the other hand, an underwater sensor rarely uses the RSS because the power of the EM wave decreases rapidly underwater. As a result, the RSS method in an underwater environment was suggested in several papers as a challenging problem [6], [18]. Our research group attempted several experiments and derived an underwater sensor model to confirm the feasibility of an underwater sensor using EM wave attenuation. First, we demonstrated the consistency of the RSS at the same distance using a radio-frequency (RF) sensor [11], and we obtained an approximate sensor model [19]. Based on these results, we conducted several experiments in an infrastructure-based underwater sensor network system [20]. Finally, we obtained an underwater sensor model and many worthwhile feasibility research results [21].

III. Derivation of EM Wave Attenuation as a Function of Distance

The EM power transmitted from one antenna to another at a distance of R is related by the Friis–Shelkunoff formula. In free space, the expression is given by

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}. \tag{1}$$

Here G_T and G_R are the gains of the transmitting and receiving antennas and λ is the free space wavelength. The gains are given with respect to a lossless isotropic radiator (which has a gain of unity). The gain includes directivity and also efficiency. In air, the resistive losses in the metal antenna are usually small and the efficiency is close to unity. In water, the efficiency is low



(a) (b)

Fig. 4. Comparison of the experimental data and the sensor model to determine whether sensor model is (a) uncalibrated or (b) calibrated.

and the wave is attenuated as it travels from the transmitter to the receiver. The Friis–Shelkunoff formula becomes

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} e^{-2R\alpha}. \tag{2}$$

Here G_T and G_R are much smaller than in (1). The attenuation coefficient α, which is the real part of the propagation constant, is given by

$$\alpha = \omega\sqrt{\epsilon\mu}\sqrt{\frac{1}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\epsilon^2}}-1\right]}. \tag{3}$$

Since we have to calibrate the antennas at each frequency and any change of antennas or water mass, we simplify the equation as follows:

$$P_R = \frac{P_T e^{-2\alpha R}}{R^2} \times c. \tag{4}$$

Constants c and α can be found with two (or more) measurements of P_R at different distances. However, the system of equations is nonlinear and the error bars on P_R tend to be constant in $\log_{10} P_R$. So we linearize the equation by taking $\log_{10}$ of both sides, expressing P_R and P_T in milliwatts so the units of $10\log_{10} P$ are decibel milliwatts (dBm). In this form, the errors are roughly equal and the equations are linear in c and α

$$10\log_{10} P_R(\mathrm{mW}) - 10\log_{10} P_T(\mathrm{mW}) + 20\log_{10} R = 10\log_{10} c - 20\alpha \log_{10} e. \tag{5}$$

We can use this result in a linear least squares analysis to find best fit values of c and α.

The calibration can be done with the 2-D localization system every time that it is operated because a 2-D localization system will require at least three anchor nodes. Thus, there will be at least three internode separations R_{ij}, and the least squares problem can be solved for c and α using only the signals transmitted between anchor nodes.

TABLE I
ANTENNA INPUT IMPEDANCE

Medium	frequency	Input impedance [Ω]
Freshwater	240MHz	$79.712 + j1.933$
	420MHz	$67.132 + j20.263$
Seawater	140MHz	$31.722 - j11.12$
	175MHz	$77.257 - j12.711$

IV. Experiment in Freshwater Condition

To verify the EM wave attenuation formula developed in Section III for an underwater environment, we have conducted two experiments. First, we measured the EM wave signal strength underwater for different distances, and compared the sensor model and the experimental results to verify the model. Second, we estimated the 2-D position information using the obtained sensor model to prove that it is effective for underwater localization.

A. *Experiment for Validating the Sensor Model in Fresh Water*

1) Antenna Setup: To propagate almost the whole EM wave underwater, many properties of the antenna and the environment should be considered. Specially, a changing medium brings about a change of wavelength and thus impedance mismatching. Moreover, a magnetic dipole has a lower near-field loss than an electric dipole and would generally be preferred for underwater use [12]. The antenna also needs to be waterproof. A new antenna satisfying the above properties has been made by outsourcing as shown in Fig. 2(a). The underwater input impedances of each antenna are shown in Fig. 2(c) and (d) and Table I.

TABLE II
TEST ENVIRONMENT PARAMETERS

	Property (symbol)	Characteristic value [unit]
Freshwater	Conductivity (σ)	0.075 [1/m]
	Permeability (μ)	1.2566×10^{-6} [H/m]
	Permittivity (ϵ)	6.8588×10^{-10} [F/m]
	Refraction index (n)	8.8
Antenna	Transmission Antenna Gain in air (G_T)	3 [dBi]
	Receiving Antenna Gain in air (G_R)	3 [dBi]
	Transmission Power (S_T)	10 [dBm]

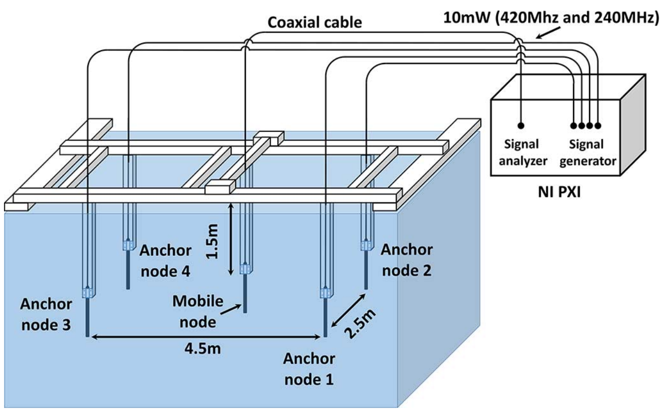


Fig. 5. Experimental environment for 2-D localization. The transmitter nodes are fixed and their positions are known. The receiver antenna is moved randomly without position information.

2) Experimental Environment: To verify the sensor model, we have set up the experiment in the underwater test facility at the Korea Institute of Robot and Convergence (KIRO, Pohang, Korea). The test tank is 12 m long, 8 m wide, and 6 m deep. To prevent EM wave reflection, the antennas were separated 1.5 m away from the wall using an aluminum experimental guide rail and were submerged 1.5 m. The antennas used in the experiment were dipole antennas with an antenna gain of 3 dBi, and the transmitting and receiving antennas were installed as shown in Fig. 3. The properties of fresh water are tabulated in Table II. The propagation constant determined from these parameters using (3) is $\alpha = 1.5118$ and 1.5112 at 420 and 240 MHz, respectively.

To ensure proper alignment between the antennas, antenna frames were used. The antenna frames were made of a dielectric material (NC nylon) to prevent multipath propagation through conductive material. The distance between the antennas R was measured as the distance between the antenna frames using a tapeline and a laser range finder. The medium inside the basin is assumed to be fresh water. EM wave generation and signal reception were carried out with a National Instruments signal generator (NI5660SA) and signal analyzer (NI5670SG). The transmitting power was set to 10 mW (+10 dBm), and two frequencies, 240 and 420 MHz, were chosen to verify the reliability of the model at various frequencies.

3) Underwater Sensor Model Experiment: To verify the sensor model, the distance between the transmitting and the receiving antenna guides is measured along with the received signal strength at the receiver for the given transmitting power signal. The distance between the antennas was incrementally increased by 0.1 m, starting at 0.4 m (because of the size of antenna frame and near-field area) up to 4 m. The RSS versus distance data was collected, and the results are shown in Fig. 4(a). A theoretical model using G_T and G_R evaluated in air with the calculated value of α is plotted as a solid line. The slopes for both the sensor model and the experimental results are almost identical; however, there was a significant offset between the sensor model and the results due to the additional near-field loss underwater [12].

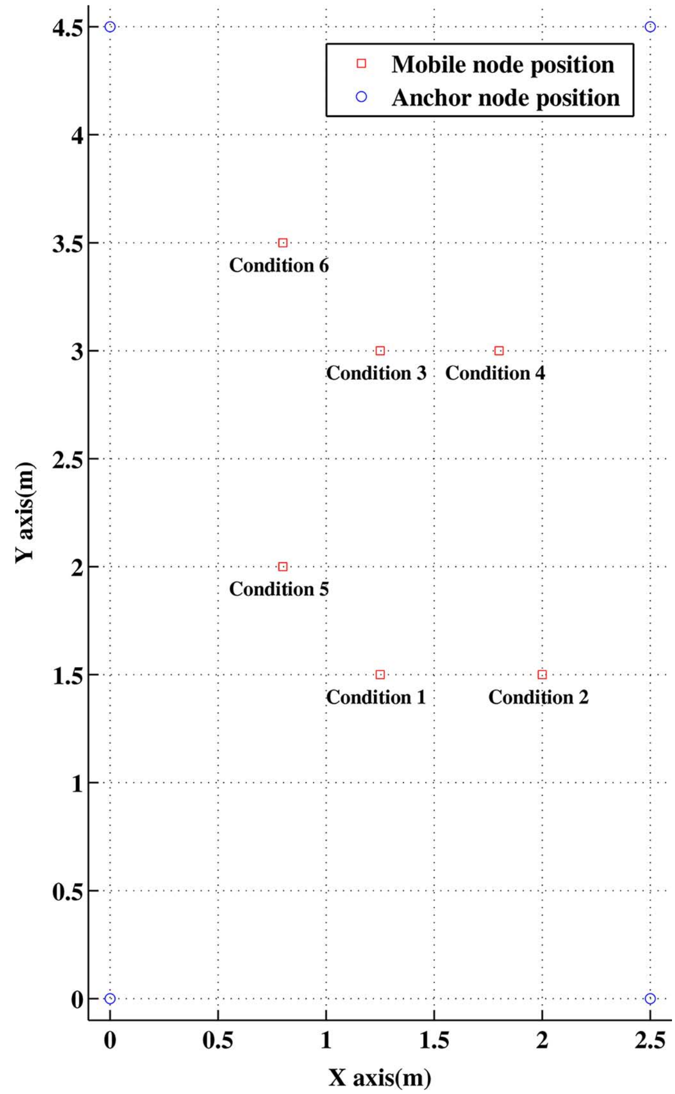


Fig. 6. Top view of the 2-D localization results.

4) Parameter Estimation of Sensor Model: To estimate parameters α and c, we measured EM wave signal strength between the anchor nodes. The experiment was conducted in a 2-D localization environment as shown in Fig. 5. Due to sensor range limitation, we fixed the mobile node at known position [1.5 m, 2 m] to use the mobile node as an anchor node. After that, the mobile node received the EM wave from other three anchor nodes. Then, we estimated c and α from the three anchor nodes to mobile antenna pairs. The fit, which is excellent,

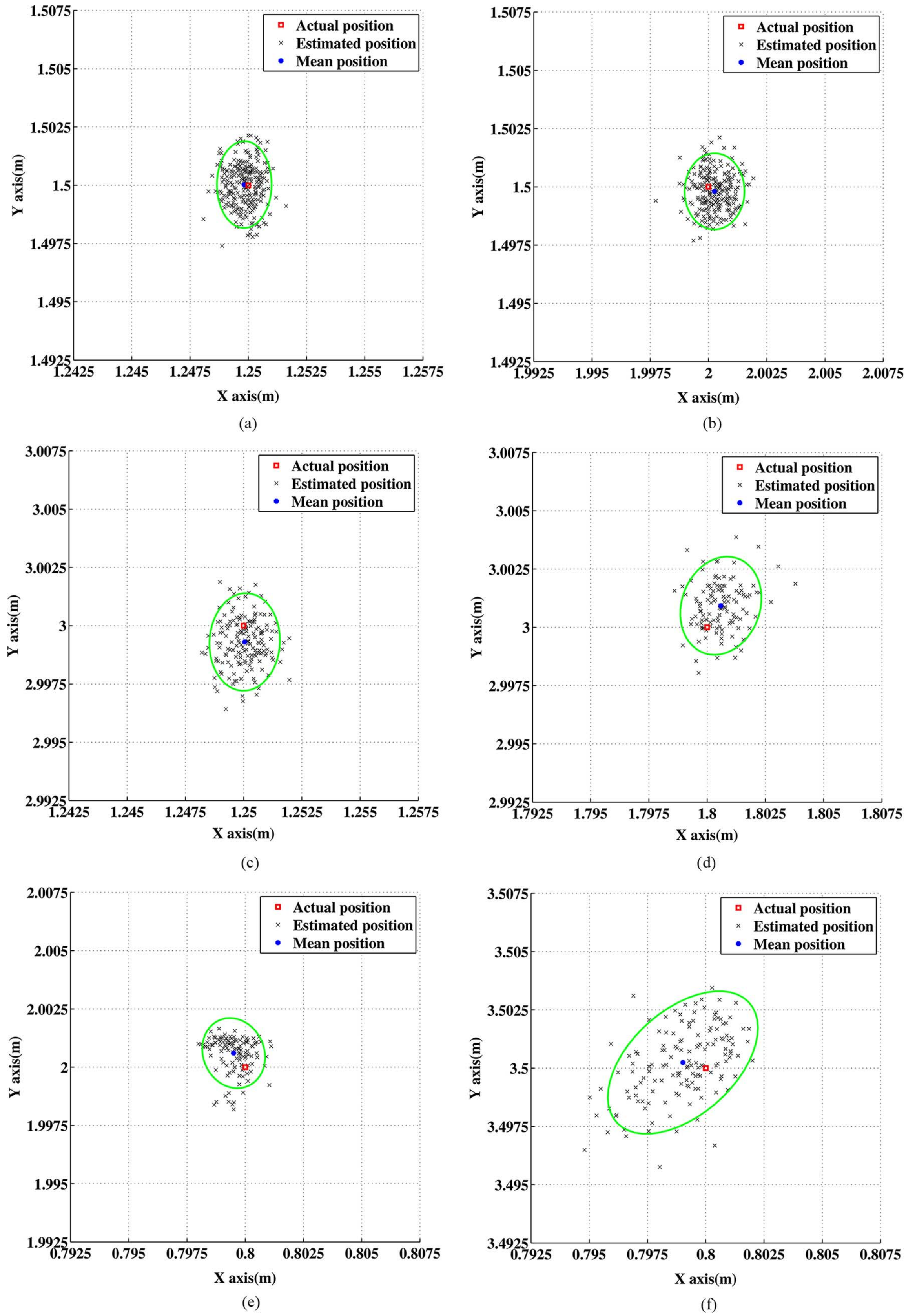
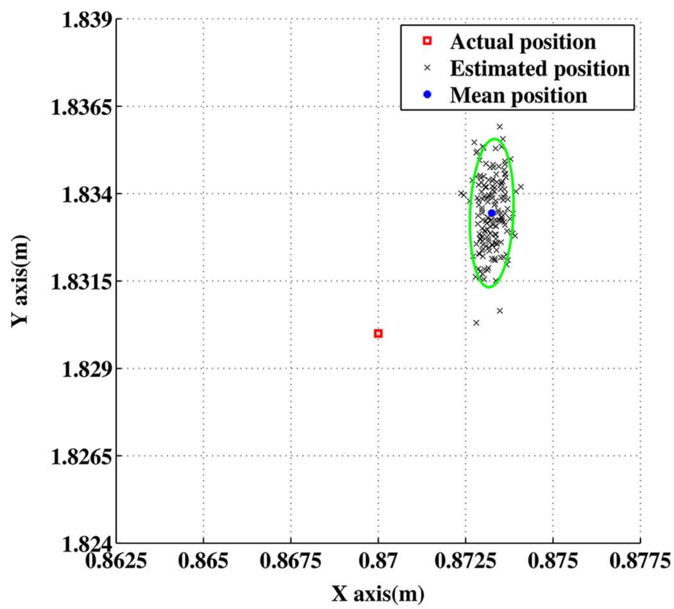


Fig. 7. Detailed localization results. These experiments are conducted with the dielectric antenna support beam. All the measured positions lie inside the covariance ellipse with a small error. The covariance ellipses of the results have a vertical major axis due to the different gaps between the anchor nodes. (a) Condition 1. (b) Condition 2. (c) Condition 3. (d) Condition 4. (e) Condition 5. (f) Condition 6.

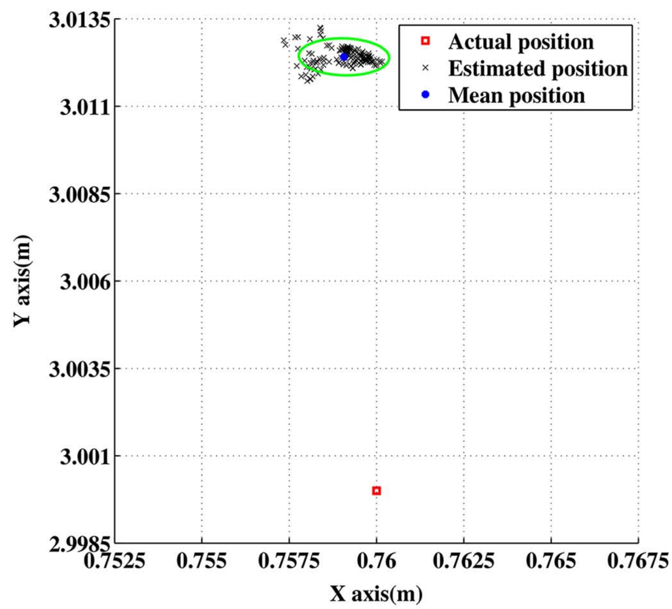
is shown in Fig. 4(b). Then, $\alpha = 1.5117$ and 1.5108 at 420 and 240 MHz, respectively, confirming that the values calculated from Table I are quite accurate. Indeed, one could simply use the alpha calculated from the water properties.

TABLE III
TWO-DIMENSIONAL LOCALIZATION CONDITIONS AND RESULTS

	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
Actual Position	[1.25, 1.50]	[2.00, 1.5]	[1.25, 3.00]	[1.80, 3.00]	[0.80, 2.00]	[0.08, 3.50]
Estimating Position	[1.2498, 1.5001]	[2.0002, 1.4998]	[1.2501, 2.9994]	[1.8006 3.0019]	[0.7995, 2.0006]	[0.7991, 3.5002]
Maximum Error	0.0032m	0.0026m	0.0034m	0.0042m	0.0026m	0.0053m
Minimum Error	0.0001m	0.0005m	0.0003m	0.0006m	0.0010m	0.0031m
RMS Error	0.0010m	0.0011m	0.0013m	0.0016m	0.0013m	0.0018m



(a)



(b)

Fig. 8. Cases of wrong localization results. The true position of (a)–(b) lie outside the covariance ellipse with a large error. These are caused by the multipath effect through the antenna support which are made of a conductive material. (a) Condition 1. (b) Condition 2.

B. Two-Dimensional Localization Experiments Using the Proposed Sensor Model in Freshwater Conditions

1) Experimental Condition and Setup: To check the sensor model performance, a 2-D localization experiment was conducted with the same conditions as the sensor model experiment. The experimental environment consisted of four anchor nodes and one mobile node with a 4.5-m-long and 2.5-m-wide rectangular test bed, as shown in Fig. 5. The anchor nodes were fixed at a specified location near the edge of the test bed and transmitted EM waves on different channels, where we knew the identification of each anchor node. The target mobile node was located in the inner area of the test bed and connected with a signal analyzer to check the RSS. Before the first 2-D localization experiment, we calibrated α and Γ using the parameter estimation scheme (these parameters are not changed until finishing the experiments due to the constant-temperature water system of the basin).

2) Experimental Procedure: Experimental procedure is as follows. After the anchor nodes and the mobile node were placed at the desired positions, we measured the distances between the anchor nodes and the mobile node using a laser range finder to determine the actual mobile node position, and double checked the distances using a measuring tapeline. Then, the four anchor nodes sequentially transmitted an EM wave at 420-MHz band frequencies with a transmitting power of 10 mW. The mobile node received 300 signals from each anchor node, and measured the amplitude of signal using signal analyzer. Next, we estimated the position of the mobile node using trilateration technique and an extended Kalman filter. Finally, we compared the estimated position with the actual position for the six different positions of the mobile node.

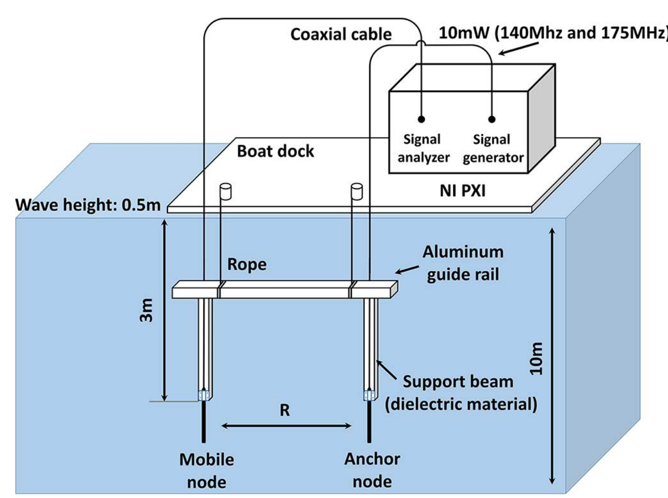
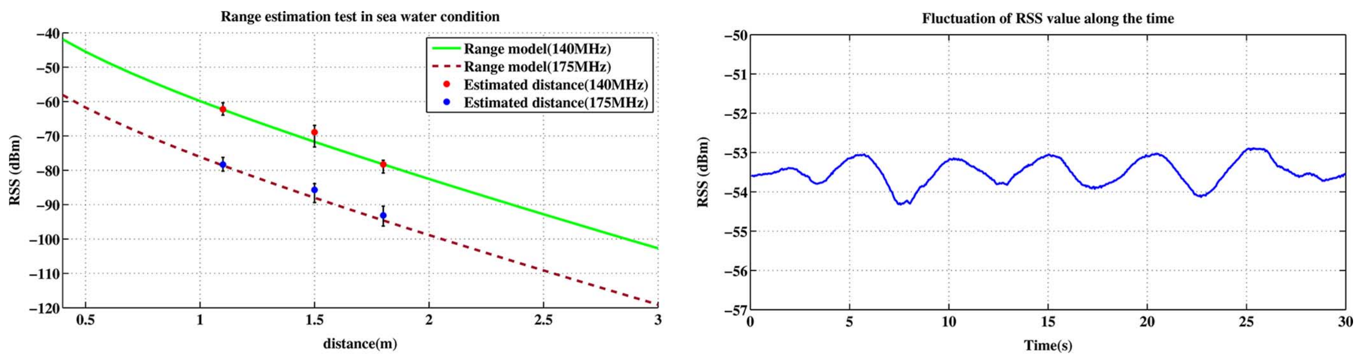


Fig. 9. Experimental conditions for the sensor performance experiment in seawater conditions (35.07462° N, 129.08577° E).



(a) (b)

Fig. 10. Seawater performance test results. In (a), each green and black solid line means the 140- and 175-MHz sensor model. EM wave showed the reliable distance measurement performance, but the results were affected by wave conditions as in (b). (a) Sensor performance. (b) Fluctuation of RSS value according to the wave.

3) Experimental Results: The experimental conditions and results are summarized in Table III and Figs. 6 and 7. The overall experimental results show very satisfactory localization results, although some experimental results have slightly out-of-center position estimation results, which still have good localization results. Almost all the localization results have covariance ellipses with major y-axis, because the height interval between anchor nodes is larger than the width interval between anchor nodes.

Even if the influence from the surrounding environment is less than that from the air, the multipath effect of the EM wave caused by the basin wall or the antenna frames can affect the RSS of the EM wave. Specifically, the multipath effect of a conductive material near nodes brings about a biased error, as shown in Fig. 8. Nevertheless, if the nodes are far from conductive material for more than half the wavelength, the localization result shows that the biased error is significantly reduced. The experimental results show very reliable 2-D position estimation with a small covariance ellipse radius. These results prove that the sensor model of EM wave can be used as a localization system in underwater environments.

V. Feasibility Test in Seawater Conditions

To investigate the sensor performance in seawater conditions, we conducted a range estimation experiment in seawater. The experimental area was a boat dock at the Korea Maritime University (35.07462° N, 129.08577° E), and the experimental depth was 10 m with 0.5-m wave height.

The experimental procedure was as follows. First, we measured the distance between the antennas, which were submerged using antenna frames at around 3 m, as shown in Fig. 9. Then, we estimated the distance using the sensor model at frequencies of 140 and 175 MHz. Finally, we repeated the same test for varying distances (1.16, 1.5, and 1.8 m).

The experimental results are shown in Fig. 10(a). They show competent distance estimation with similar tendency. However, there exist some biased errors between the estimated and measured values. We assume the errors are caused by the sea waves, as shown in Fig. 10(b), because the RSS fluctuation frequency ($\approx$0.2 Hz) is similar to the normal seawater wave frequency. The supporting rope and aluminum guide rail may experience vibration and fluctuation by the sea waves. As a result, the estimated distances and RSS amplitude are periodically changed, and changes of estimated distances are synced with the wave cycle. Nevertheless, we need more experiments to find the cause of biased error thoroughly.

VI. Conclusion and Future Work

In this paper, we proposed a novel distance sensor using EM wave attenuation. We developed and tested an underwater EM wave sensor model using a least square method to estimate model parameters. Finally, we conducted 2-D localization and seawater distance estimation experiments in order to check the range sensing performance. These experimental results show that the proposed sensor model can estimate the real distance with almost 0.1% error for the experiments in this paper with the range of about 4 m.

For future works, we will conduct more experiments to consider the effects of the surrounding environment. We showed the effect of conductive material in 2-D localization experiment, as shown in Fig. 8. It suggests that the sensor performance is affected by obstacles, and further research is required to enhance performance. After this enhancement, we plan to conduct 3-D localization and a dynamic environment localization with wireless sensor modules. It is hard to estimate the RSS value according to the vertical angle due to the antenna pattern change in lossy medium. So, we set up the sensors on several horizontal planes in target space, and we will estimate the position using sensor fusion with inertial measurement units or depth sensor.

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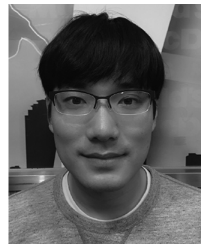

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