Validation of Pseudo-Scale Model for the Air-Sea Two-Layer Near-Field Problem by Using FDTD Simulations and Measurements in a Tank

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***Abstract*— A pseudo-scale model for the air-seawater two-layer problem, adjustable in two parameters, a scale factor with respect to length and a conductivity multiplier, is examined by using the results of FDTD simulations and scaled measurements in a tank. For the conversion of the sea region of the model, it can be derived assuming that the entire region is the sea, and for the conversion of the air region, it is assumed to be the extreme near-field of the source. The behavior of the electromagnetic field in the air region just above the sea surface can be validated by examining the field distribution in the region where lateral waves are dominant. The distributions of the dominant electric field component before and after the scale conversion almost coincide in the direct wave and lateral wave regions. This fact confirms the validity and effectiveness of the proposed pseudo-scale model.**

***Index Terms*—air-sea two-layer problem, near-field region, pesudo-scale model, FDTD simulations, scaled measurements.**

I. INTRODUCTION

Recent developments in computing, communication, and measurement technologies have made it possible to receive electromagnetic waves at very weak levels, which were previously considered difficult to measure. In general, undersea has been considered unsuitable for communication using radio waves due to the larger attenuation constant at higher frequencies, and even now there is no way to change this physical characteristic. Recently, transmission tests between loop antennas or half-sheath dipole antennas were attempted in marinas or open sea region near the quay [1-3]. By limiting the communication range and using not only direct waves in the sea but also lateral waves passing over the sea surface, it is possible to communicate with radio waves through the sea, even over short distances [4]. The authors have been studying the effectiveness and feasibility of a system for locating divers in shallow water who are searching for victims in distress by receiving radio waves from divers' transmitters with receivers attached to buoys on the sea surface, using electromagnetic field simulations based on the FDTD method [5]. Of course, we have been attempting some actual underwater experiments to confirm the operation of this system in the sea [6]. However, the cost of renting cranes, vessels, and barges is very expensive, and it is not possible to conduct cut-and-try experiments many times, which is a major obstacle in advancing our study.

In order to reduce this enormous cost, we will consider scale models necessary to conduct early-stage cut-and-try experiments in the laboratory. A compilation of scale models for electromagnetic fields was published in [7]. The length l is converted to l' via a scale factor n, i.e., $l' = l/n$. In the well-known geometrical scale model [8], the angular frequency should be multiplied by n, with $\omega' = n\omega$, and the conductivity by n, with $\sigma' = n\sigma$, without changing the permittivity and permeability. Our original model assumes a frequency of 10 kHz and deals with a range of $50\ \mathrm{m} \times 50\ \mathrm{m} \times 10\ \mathrm{m}$ of seawater [5]. For example, assuming a $1\ \mathrm{m}^3$ water tank, the scale factor would be $n = 50$, and the conductivity after scale conversion would have to be 50 times the conductivity of the original seawater (e.g., 4 S/m), but such a salinity of salt water is not practicable. For such a problem, it is known that if the contribution of the displacement current can be neglected for the conduction current in the sea, the scale model can be reconstructed by neglecting the term which includes the permittivity in Maxwell's equations [9,10]. Hereafter, the condition under which the contribution of the displacement current can be neglected is called the "conducting medium condition." Under this condition, the pseudo-scale model can be realized by determining the conductivity σ' and angular frequency ω' after scale conversion so that $\sigma'\omega' = n^2\sigma\omega$ when the scale factor is n [9].

The authors also have used the pseudo-scale model with $\sigma' = \sigma$ that does not change conductivity before and after conversion, based on the fact that the frequency characteristic of the conductivity of seawater shows a constant value at frequencies up to 400 MHz [11]. In this specific scale model, the angular frequency after scale conversion is determined by $\omega' = n^2\omega$ [12]. The conductivity-invariant property [11] is very useful for measurements in a tank, because of putting the seawater in the tank as it is. Field simulations of the model using the FDTD method and measurements in the tank have confirmed that the field behavior obtained by the scale model is almost the same as that of the original model, including the air region above the sea surface [12]. Experiments on the pseudo-scale model with $\sigma' = \sigma$ using circularly polarized cross dipole antennas as the transmitting and receiving antenna were also studied [13]. The effect of the tank wall, which is not considered in the paper, is not necessarily negligible. For this reason, it is required to increase the scale factor and conduct the scale model measurements in a region away from the tank wall. However, increasing the scale factor n means increasing the angular frequency in proportion to n^2, which means that the loss tangent $\tan\delta$ of the medium, i.e., a measure of the ratio of the conducting current contribution to the displacement current contribution, becomes smaller. We should be aware of the fact that the scale factor n is too large to satisfy the conducting medium condition.

As a solution to the above problem, this paper proposes a new method to satisfy the conducting medium condition after scale conversion and confirms its effectiveness by FDTD simulations and measurements for the pseudo-scale model in the tank. The new proposal is to set $\sigma' = m\sigma$ as the conductivity after scale conversion in the relation $\sigma'\omega' = n^2\sigma\omega$. The angular frequency is converted as $\omega' = (n^2/m)\omega$, and $\tan\delta$ becomes larger than before scale conversion. The case of $m = n$ is identical to the geometrical scale model, but of course, m should be selected so that the salt water has a practicable salinity.

II. Brief Derivation of Pseudo-Scale Model

For simplicity, we consider a uniform medium satisfying the conducting medium condition, $\tan\delta \gg 1$. Let ω be the angular frequency, ε and σ be the permittivity and conductivity of the medium, we can find that the conducting medium condition is equivalent to $\sigma \gg \omega\varepsilon$. In this case, the Maxwell's rotation equations become [9]

$$\left.\begin{aligned}\nabla \times \boldsymbol{E} &= -j\omega\mu\boldsymbol{H}\\ \nabla \times \boldsymbol{H} &= \sigma\boldsymbol{E}\end{aligned}\right\}, \tag{1}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are electric and magnetic fields, and μ is the permeability of the medium. Converting the length l to $l' = l/n$, yields $\nabla' = n\nabla$, where n is scale factor. Also, the prime symbol ($'$) is added to the quantities after scale conversion. Then, the converted Maxwell rotation equations become

$$\left.\begin{aligned}\nabla' \times \left(\frac{n}{m}\boldsymbol{E}\right) &= -j\left(\frac{n^2}{m}\omega\right)\mu\boldsymbol{H}\\ \nabla' \times \boldsymbol{H} &= (m\sigma)\left(\frac{n}{m}\boldsymbol{E}\right)\end{aligned}\right\}. \tag{2}$$

By putting $\omega' = (n^2/m)\omega$, $\sigma' = m\sigma$, $\boldsymbol{E}' = (n/m)\boldsymbol{E}$, and $\boldsymbol{H}' = \boldsymbol{H}$, (2) become the same as (1). The above relationships for the quantities give the conversion rule in the pseudo-scale model as listed in TABLE I.

It should be pointed out that the above conversion rule does not generally work in the air region. We are interested in conversion rule for the near field which is produced by an infinitesimal dipole source. Therefore, the field can be evaluated as the static field even if the frequency is changed.

TABLE I. Conversion Rule of Quantities for Scale Models

Quantity	Original Model	Geometrical Scale Model [5]	Pseudo-Scale Model
Length	l	l/n	l/n
Angular frequency	ω	$n\omega$	$(n^2/m)\omega$
Electric field	$\boldsymbol{E}$	$\boldsymbol{E}$	$(n/m)\boldsymbol{E}$
Magnetic field	$\boldsymbol{H}$	$\boldsymbol{H}$	$\boldsymbol{H}$
Permittivity	ε	ε	ε
Permeability	μ	μ	μ
Conductivity	σ	$n\sigma$	$m\sigma$
Loss tangent	$\tan\delta$	$\tan\delta$	$(m/n)^2\tan\delta$

III. FDTD Simulation

Fig. 1 shows an air-sea two-layer problem such that there is an air region above a sea region [5]. An xy-plane is chosen on the sea surface, and the range of x and y is assumed to be $|x|, |y| \leq 50$ m. The depth of the sea region is assumed to be 9 m. We consider a model in which a diver's transmitter radiates electromagnetic waves into the sea by means of an infinitesimal horizontal dipole oriented along the x-axis and transmits the x-polarized component in the plane of z m below the sea surface. This model is referred to as the original model, with scale factor of $n = 1$. We assume that the real part of complex dielectric constant of the seawater is 80 and the conductivity is 4 S/m. We simulate the distribution of the x-component of the electric field (E_x distribution) by using the FDTD method for the original model. Fig. 2 shows the E_x distribution in the plane of $z = 4$ m when assuming the CW operation. It is the basis for distribution comparison in this paper. In this distribution, there is a direct wave region due to the x-directed dipole centered at $x = 0$ m and $y = 20$ m on the sea surface. Outside of this region, there is a region with less distance attenuation than the direct wave. This is the contribution from lateral waves. In other words, in the region near the dipole, not only direct waves but also lateral waves with the sea surface as a partial path become dominant [4].

In this paper, we consider a pseudo-scale model with scale factor of $n = 200$ and conductivity multiplier of $m = 2$ for the original model. The reason for setting $n = 200$ is to minimize the effect from the tank wall as described in next section, and the reason for setting $m = 2$ is to satisfy the conducting medium condition. The values of length, frequency, conductivity, and $\tan\delta$ before and after scale conversion are listed in TABLE II. Fig. 3 shows a FDTD simulation result for the E'_x distribution of the pseudo-scale model in the plane of $z = 20$ mm. Fig. 4 shows a distribution of dB difference between Figs. 2 and 3, defined as

$$\Delta E_{x,\mathrm{dB}}^{(\mathrm{fdtd})} = 20\log_{10}\left|\frac{(m/n){E'_x}^{(\mathrm{fdtd})}}{E_x^{(\mathrm{fdtd})}}\right|, \tag{3}$$

where the superscript (fdtd) denotes the quantity obtained by the FDTD simulation.

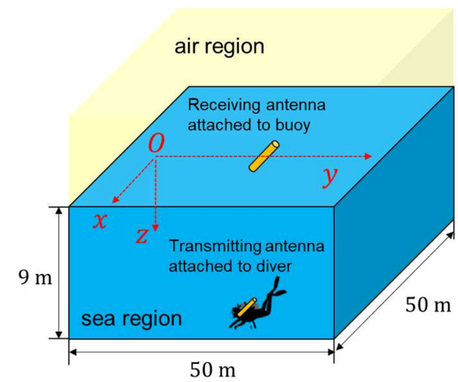


Fig. 1. Air-sea two layer problem for locating the diver [4].

TABLE II. VALUES BEFORE AND AFTER SCALE CONVERSION FOR $n = 200$ AND $m = 2$.

Quantity	Original Model	Pseudo-Scale Model
Length	20 m	100 mm
Frequency	10 kHz	200 MHz
Conductivity	4 S/m	8 S/m
Loss tangent	9.71×10^4	10.6

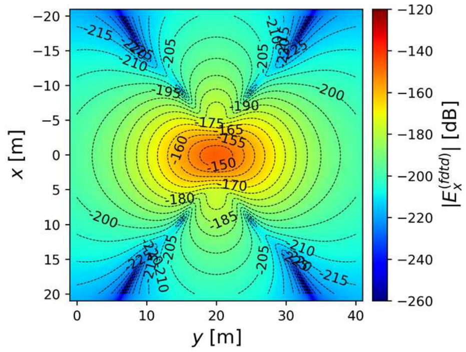


Fig. 2. E_x distribution for the original model of $n = 1$ in the plane of 4 m depth by using FDTD simulation.

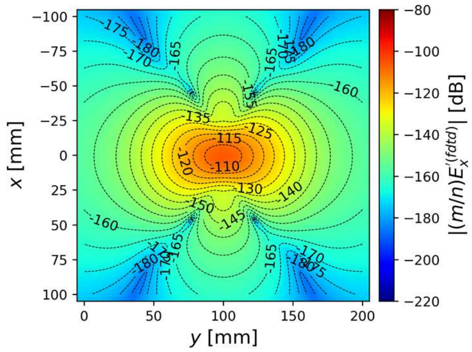


Fig. 3. E_x distribution for the pseudo-scale model of $n = 200, m = 2$ in the plane of 20 mm depth by using FDTD simulation.

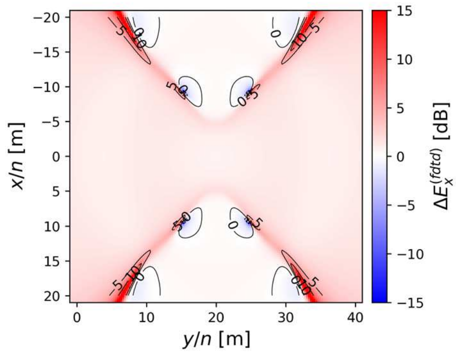


Fig. 4. dB difference between the original model of $n = 1$ and the pseudo-scale mode of $n = 200, m = 2$ in the plane of $(4/n)$ m depth by using FDTD simulation.

In common with Figs. 2 and 3, there are nulls due to the presence of lateral waves in the direction of $y = \pm x/\sqrt{2}$ [14]. However, if these nulls are excluded, Fig. 4 shows that the dB

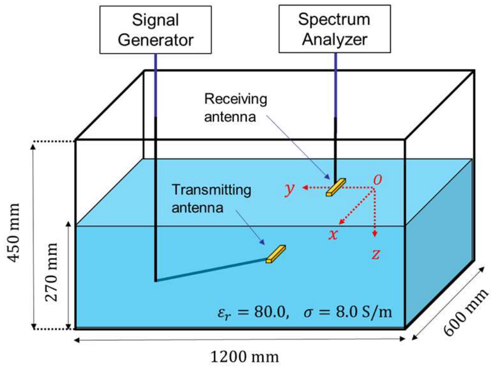


Fig. 5. Experimental setup for pseudo-scale model of air-sea two layer problem.

difference including the scale effect with respect to the electric field is almost 0 dB so that the validity of the pseudo-scale model can be demonstrated from the results of FDTD simulation.

IV. SCALED MEASUREMENTS IN THE TANK

As another validation of the pseudo-scale model, we compare the simulated result of the original model of $n = 1$ with the measured results of the pseudo-scale model. The scale factor n and conductivity multiplier m for the pseudo-scale model are the same as in Section III. The conductivity of the salt water used is $\sigma = 8.0$ S/m, or the salinity 5.65 % at 20°C, which is twice the conductivity of the original model. As shown in Fig. 5, a tank with a dimension of 1200 mm × 600 mm × 450 mm is filled to a height of 270 mm with the salt water and three stepping motors are used to move the transmitting horizontal dipole antenna. Electromagnetic waves are transmitted from the transmitting dipole antenna and received by a receiving horizontal dipole placed just below the water surface. The transmitting antenna is moved every 10 mm over a range of $|x| \leq 100$ mm, $0 \leq y \leq 200$ mm, and the depth z is changed every 5 mm from 5 mm to 45 mm. With such an experimental system, we measured received distribution (E_x distribution) corresponding to the same E_x distribution as simulated in section III.

Fig. 6 shows a measured distribution in the plane of $z =$ 20 mm depth for the pseudo-scale model of $n = 200$, $m = 2$. Fig. 7 shows a distribution of the dB difference between Figs. 2 and 6, $\Delta E_{x,\mathrm{dB}}^{(\mathrm{mea})}$, when the scales of Figs. 2 and 6 are matched considering the scale factor and the levels are adjusted so that the dB difference is 0 dB at the peak level. Compared to the original model, the dB difference as shown in Fig. 7 is not as close to 0 dB as the comparison with the simulated values as shown in Fig. 4, partly because the depth of the nulls caused by lateral waves is smaller than simulated one and partly because the measured contours are slightly distorted in the lateral wave region. In general, however, the behavior of $|E_x|$ in the simulated original model is consistent with the measured pseudo-scale model, except in the vicinity of the nulls. One possible reason for the lack of agreement in the lateral wave region is that some positions of the secondary sources for the lateral wave on the water surface deviates from the simulated ones due to reflections from the tank wall or the rigidity of the antenna fixture. Further study should be required to determine the reason of this discrepancy.

Hereafter, we will compare the three E_x distributions in the plane of $z = (4/n)$ m, i.e., the simulated E_x distribution for the original model of $n = 1$ and the simulated and measured E_x distributions for the pseudo-scale model of $n = 200, m = 2$, along certain straight lines. Figs. 8 (a) and (b) show graphical comparisons of $|E_x|$ along $x = 0$ m and $x = (10/n)$ m, respectively. The simulated $|E_x|$ distributions of the original and pseudo-scale models can be regarded as identical. The measured values tend to shift slightly near the peak as shown in Fig. 8(a), but are consistent with the simulated values. Figs. 9 (a) and (b) show graphical comparisons of $|E_x|$ along $y = (20/n)$ m and $y = (30/n)$ m, respectively. The simulated $|E_x|$ distributions of the original and pseudo-scale models are almost identical. The differences are only observed near the nulls as shown in Fig. 9(b). For $y = (20/n)$ m, the simulated and measured distributions are in general consistent, but small nips near the peak cannot be traced in the measurements. For $y = (30/n)$ m, simulated and measured distributions are nearly identical except for the differences near the nulls.

As described above, the scaled measurements in the tank confirm the validity and effectiveness of the proposed pseudo-scale model.

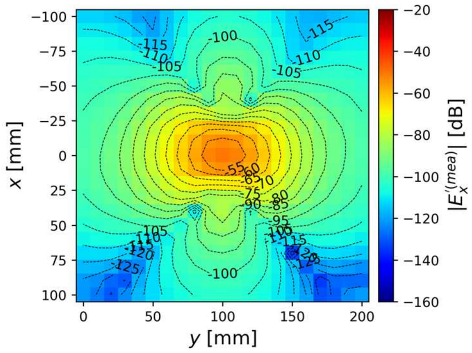


Fig. 6. E_x distribution for the pseudo-scale model of $n = 200, m = 2$ in the plane of 20 mm depth by measurement in the tank.

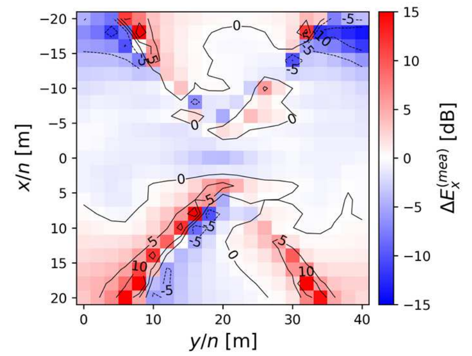
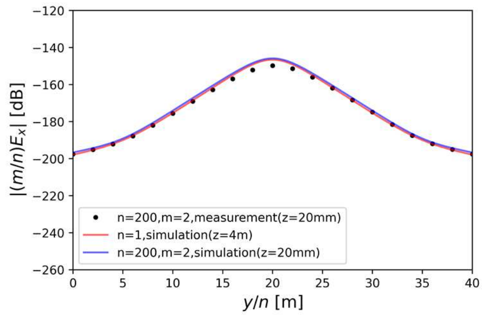
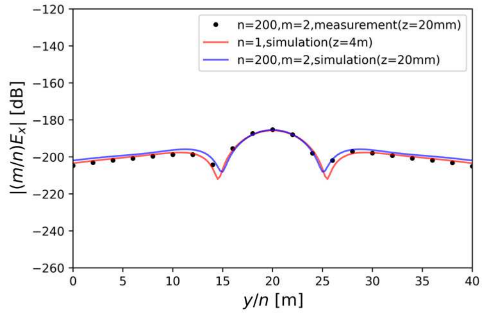


Fig. 7. dB difference between the original model of $n = 1$ by using FDTD simulation and the pseudo-scale model of $n = 200, m = 2$ by measurement in the tank in the plane of $(4/n)$ m depth.

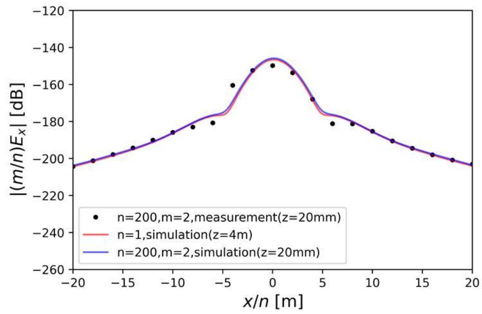


(a) $|(m/n)E_x|$ on $x = 0$ m, $z = (4/n)$ m

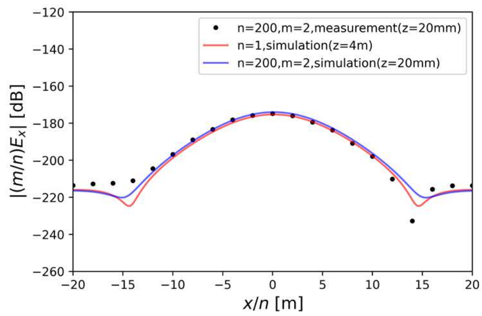


(b) $|(m/n)E_x|$ on $x = 10/n$ m, $z = (4/n)$ m

Fig. 8. $|E_x|$ comparison of the original model of $n = 1$ and the pseudo-scale model of $n = 200, m = 2$ on $x = 0$ m, $z = (4/n)$ m and $x = (10/n)$ m, $z = (4/n)$ m.



(a) $|(m/n)E_x|$ on $y = (20/n)$m, $z = (4/n)$ m



(b) $|(m/n)E_x|$ on $y = (30/n)$m, $z = (4/n)$ m

Fig. 9. $|E_x|$ comparison of the original model of $n = 1$ and the pseudo-scale model of $n = 200, m = 2$ on $y = (20/n)$ m, $z = (4/n)$ m and $y = (30/n)$ m., $z = (4/n)$ m.

V. CONCLUSIONS

By using the pseudo-scale model specialized for conducting medium, we showed that scaled measurements on the air-sea water two-layer problem are possible in a tank that can be set up in a laboratory. It is required that the seawater after scale conversion is satisfied with the conducting medium condition in the model. Also, we showed that adjusting the value of the conductivity is an effective means to achieve this conversion. Unfortunately, the pseudo-scale model as a key principle in this paper was derived by assuming a single conducting medium. So, future work is to derive and examine the pseudo-scale model based on the expressions of electro-magnetic fields in the air-sea two-layer problem using the Sommerfeld integral.

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