3D Measurement of Transmission between Small Dipole Antennas Using Pseudo Scale Model for Underwater Positioning System in kHz Band

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Abstract To construct the underwater positioning system operated in the kHz band, we measure the transmission coefficient between two sheathed dipole antennas in the salt water using the pseudo scale model for the conducting medium, which is proposed by us. The transmitting antenna is placed just beneath the interface between air and salt-water regions and the receiving antenna is three-dimensionally moved in the salt-water region. The resulting distance characteristic is affected by the direct wave as well as the lateral wave which travels up to a point on the surface, along the surface in the air region, and down to the receiving antenna.

Keyword Underwater, Positioning System, Pseudo Scale Model, Sea Water, Direct Wave, Lateral Wave

1. Introduction

The authors have studied the position ranging system in sea water using low frequency radio waves [1]-[4]. Radio waves in sea water has been regarded to be unsuitable for long distance communication due to its large attenuation. However, the authors think that it is time to reexamine the use of radio waves in sea water using state-of-the-art of wireless and digital communication technologies and computational electromagnetics. In recent years, the JAMSTEC (Japan Agency of Marine-Earth Science and Technology) has conducted propagation tests in a water tank filled with sea water in the MHz band using loop antennas [5]. Also propagation tests were carried out in England [6].

Back in the era, research peaked in the 1960s focused on radio wave application in sea water was conducted. The epoch-making topic of the time was that the distance characteristics between the antennas placed beneath the sea surface could be separated into contributions of direct and lateral waves. This fact was theoretically and experimentally verified [7],[8]. The direct wave is a wave traveling linearly in sea water between the antennas, and the lateral wave is a wave that travels vertically upward from the transmitting antenna to the sea level just above it, goes out to sea level, travels right above the receiving antenna along the sea surface, and travels vertically downward from the sea surface to the receiving antenna. If the attenuation experienced by the lateral wave is less than that by the direct wave, the lateral wave is dominant and received. In other words, this means that it is more advantageous to communicate in the air rather than directly propagating in the seawater. This phenomenon is observed when the antenna is installed at a point not far from the sea surface.

Our position ranging system using radio waves, is aimed to support ship overturn in shallow water. We use a low frequency in the kHz band. It is assumed that the diver conducts a search operation at 1 m to 10 m below the sea level. To realize our proposed system, we have studied on the following issues.

(a) Radio propagation characteristics in sea water, including frequency characteristic, communication distance, mathematical model [1],

(b) Positioning algorithm in sea water, including inverse functional utilization of amplitude damping distance characteristics considering lateral wave [2],

(c) Antenna design and measurement method using pseudo scale model [3].

In this paper, we will experimentally examine propagation in seawater near sea surface, which is the basis of our positioning algorithm, using a pseudo scale model. First, we explain the basic idea of positioning algorithm and its numerical simulation model. Next, we introduce the pseudo scale model and show three-dimensionally measured distance characteristic of the transmission coefficient between the transmitting and receiving dipole antennas in the pseudo scale model.

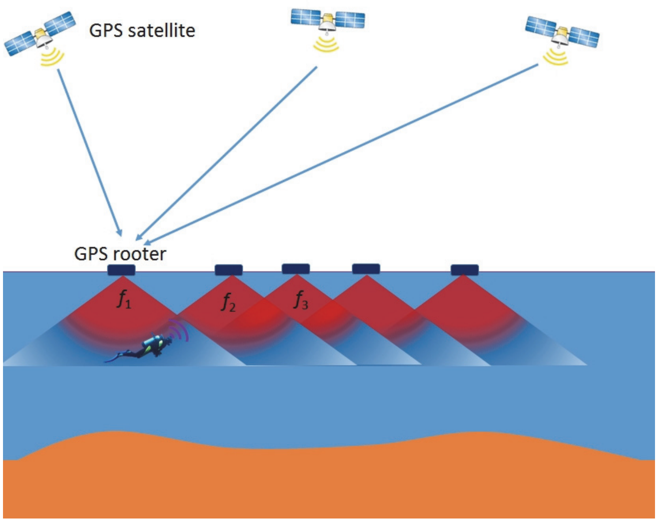


Fig.1. Proposed positioning system in sea water.

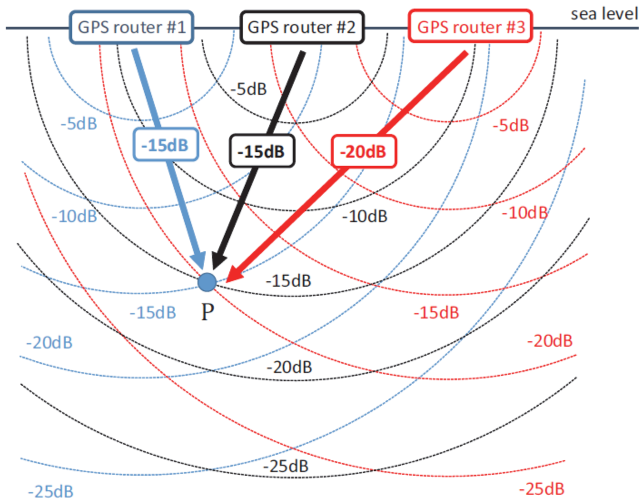


Fig.2. Basic principle of position ranging in sea water using more than three GPS routers.

2. Positioning Ranging in Sea Water

2.1. Proposed Positioning Ranging

GPS routers installed on the sea surface determine their own position with a signal from the GPS satellite and receive the amplitude information of the signal emitted from the diver transmitter as shown in Fig. 1 [1],[2]. The position in sea water is specified by collecting router position and received amplitude information among multiple GPS routers. To explain our basic principle, we assume that the transmitting antenna in the diver transceiver and the receiving antenna in the GPS router are omnidirectional and there is no lateral wave through the sea surface. There are three GPS routers on the sea surface, and the receiving amplitude from the diver transmitter can be measured. Each GPS router can identify the spherical surface on which the diver transmitter resides from its received amplitude level. The point of intersection of the spherical surface with respect to the receiving amplitude levels in the three GPS routers would be the position of the diver transceiver as shown in Fig. 2. In practice, various error factors are interposed so that diver transceivers would exist within the range that can be regarded as an intersection point. If the search activity in the shallow is assumed, the signal from the diver transceiver may be received by the GPS router as a lateral wave rather than a direct wave [2]. Moreover, when assuming the dipole antenna on the side of the GPS router, it is required to calibrate the received power considering its directivity.

2.2. Simple Simulation Model

Assuming plane wave propagation, at the frequency of10 kHz, the value of the attenuation constant in sea water is 3.5 dB/m so that the wave can reach 30 m or more. Focusing on this fact, we have studied our positioning system at the frequency of 10 kHz.

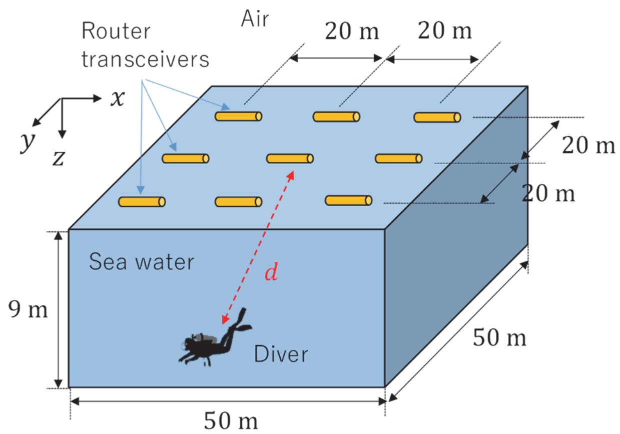


Fig. 3. Simple simulation model for position ranging. Three dipole antennas on the sea surface receive the signals from the diver transceiver in the sea water.

As shown in Fig. 3, in our simple simulation model, as a substitute for the router, a dipole antenna oriented in the same direction is arranged at intervals of 20 m on the sea surface. Also, as a diver transceiver, a dipole antenna is placed in sea water. As an initial study, the orientation of the antenna is assumed to be parallel to the sea surface. In the simulation, the seawater occupies a volume of 50 m × 50 m × 9 m. As the position of the diver antenna can be moved at an interval of 1 m, and the three-dimensional distribution of the transmission characteristics between the antennas is calculated by the FDTD method. And we can apply the aforementioned positioning algorithm to the numerical distribution [2].

3. Laboratory Experiment with Pseudo Scale Model

3.1. Pseudo Scale Model

As a scale model of the electromagnetic field, it is well known that the frequency becomes n times when the dimension is $1/n$ times [9]. In this scale model, the permittivity and permeability of the medium are not changed, but the conductivity is multiplied by n. For 1 MHz operation corresponding to the scale model of 10 kHz operation, however, the conductivity should be multiplied by 10^2. Since the conductivity of sea water at 10 kHz is about 4 S/m, it is necessary to prepare a liquid of 4×10^2 S/m at 1 MHz. It is not realistic to prepare equivalent salt water because of its saturation.

The pseudo scale model proposed by the authors is a practical solution to the above difficulty [3]. This is because the pseudo scale model is based on the Maxwell's equation in the conductive medium ignoring the displacement current term. In the pseudo scale model, the frequency becomes n^2 times when the dimension is $1/n$ times. Not only the permittivity and conductivity but also the conductivity need not be changed. That is, seawater experiments at 10 kHz may be simulated by laboratory experiments at 1 MHz using the seawater of the same conductivity. It should be noted that it is essential to use a higher frequency to reduce the size.

3.2. Measurement Results

The scale factor should be set to $n = 200$ to make measurements with the pseudo scale model for the previous simulation model in a water tank with dimensions of 600 mm × 295 mm × 360 mm that can be easily installed in the laboratory. The frequency of 10 kHz in the simulation model is converted to 400 MHz in the pseudo scale model. The real part of the dielectric constant and conductivity of the salt water were measured as 71.03 and 4.034 S/m at the liquid temperature of 21.6 °C.

A dipole antenna is a balanced feed, half-sheathed dipole antenna [4] with a feeding portion covered with a silicon sealant, and a 180° hybrid junction is used as a balun. The dipole antenna is 50 mm long, the sheath is about 10 mm long and 3 mm in diameter.

As shown in Fig. 4, the transmitting dipole antenna is installed on the water surface. Its center is placed as the origin of the coordinate system, and the x, y, and z axes are defined as shown in Fig. 4. The receiving dipole antenna is given its center at a point (x, y, z) and can be moved in the salt water three-dimensionally by controlling the three sliders. The movable range of the point (x, y, z) is $-80\text{ mm} \le x \le 80\text{ mm}$, $0\text{ mm} \le y \le 200\text{ mm}$, and $5\text{ mm} \le z \le 85\text{ mm}$ at an interval of 5 mm. The transmitting and receiving dipole antennas are parallel to the x axis.

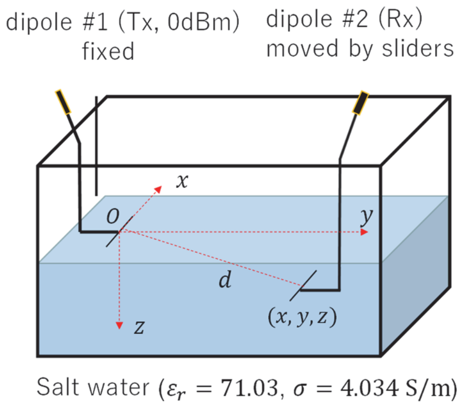
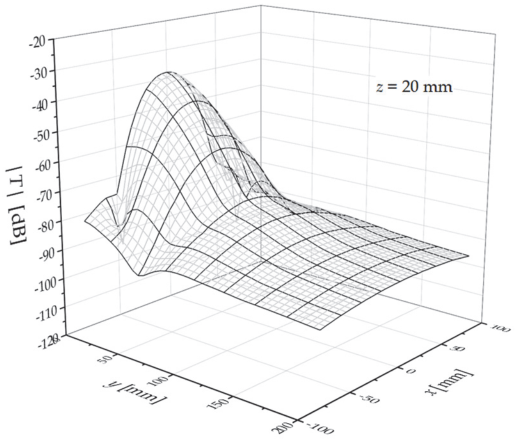


Fig. 4. Pseudo scale model for simulation model (scale factor: $n = 200$).

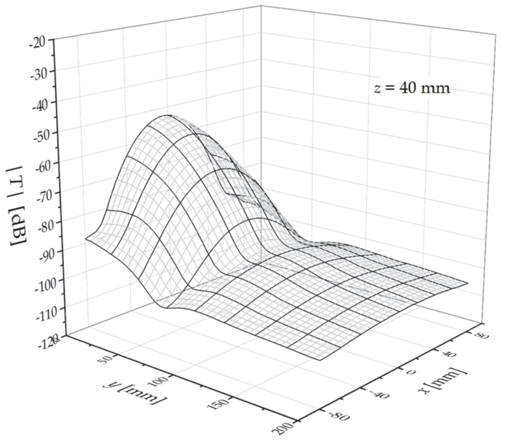
The input power to the transmitting antenna including the hybrid junction is 0 dBm, and the output power at the port of the receiving antenna including the hybrid junction is measured with a spectrum analyzer.

Fig. 5 shows a plot of $|T|$ in the two planes of $z = 20$ mm and $z = 40$ mm parallel to the xy plane, where the magnitude of the transmission coefficient $|T|$ is defined as the ratio of the received power to the input power. We can observe two different profiles. One is a profile up to the distance of approximately 100 mm from the transmitting antenna and is formed by the direct wave produced by the transmitting antenna. This wave does not spread to a simple concentric spherical shape, but has an angular characteristic, that is, directivity. When the distance from the transmitting antenna exceeds 100 mm, the slope of $|T|$ becomes considerably flat. This is because $|T|$ is dominated by attenuation due to a lateral wave which is almost determined by the distance between the transmitting/receiving antenna and water surface. This is also apparent from the fact that the value of $|T|$ on the plane of $z = 40$ mm is smaller than $z = 20$ mm.

Fig. 6 shows the distance characteristic of $|T|$ in the yz plane when the depth z of the receiving antenna is used as a parameter, where d on the horizontal axis is the distance between the transmitting and receiving antennas, and is given by $d = \sqrt{y^2 + z^2}$. $|T|$ can be classified into a region attenuated by d^{-3} and a region including branched curves. If the attenuation of the lateral wave is smaller than the direct wave, the lateral wave dominates and the slope of $|T|$ becomes small. The dB value of $|T|$ in this region is proportional to the depth z for $z \le 40$ mm. However, the dB value of $|T|$ is no longer proportional to the depth z for $z \ge 50$ mm. This difficulty would be caused by the measurement limit of the spectrum analyzer and could be solved by increasing the input power.



(a) $z = 20$ mm



(b) $z = 40$ mm

Fig. 5. Distribution of transmission coefficient between the antennas in a plane parallel to the xy plane. Two different slopes are observed.

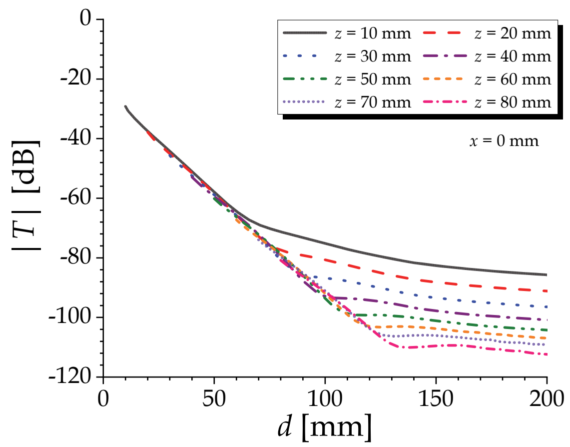


Fig. 6. Distance characteristic of transmission coefficient between the antennas as a function of the distance d. There are two types of the curves, directed wave and lateral wave.

4. Conclusions

In this paper, we described the concept of the seawater positioning system using the amplitude information. And we introduced the pseudo scale model enabling the measurement in the laboratory of the electromagnetic wave propagation in the seawater, and showed an example of its use. The transmission characteristics between transmitting and receiving antennas in sea water were measured in a pseudo scale model constructed with a scale factor of $n = 200$. When considering the positioning system algorithm, it is possible to experimentally evaluate the effect of the lateral wave and the directivity of the antenna. These effects have already been clarified by our own electromagnetic field simulation. Since the dielectric constant and conductivity of the seawater have frequency characteristics, the scale factor should be more reduced, or the frequency should be more lowered for accurate modeling the positioning system.

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