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MODELING AND SIMULATION OF DUAL SOUND LOCATION OF UNDERWATER ULTRASOUND DETECTOR UNDER VOLUME REVERBERATION

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ABSTRACT

Aiming at the request of fast target location in underwater ultrasound detector, the dual sound location algorithm of close range detecting is proposed. By estimating the pressure difference and the time difference of dual sensors, the algorithm puts forward the pressure difference location model and the time difference location model, and derives the analytic solutions of real-time location. The mirror fuzzy problem of the linear array is resolved by dual sensors rotating 90 degrees. The problem that the target is unable to locate when it is located on the perpendicular bisector is solved by dual sensors rotating angle. The volume reverberation model is established. Simulation results show that the algorithm under the lower reverberation can achieve better location. The algorithm can meet high sensitivity and fast response requirements of underwater ultrasound detector close range detecting.

Keywords: *underwater ultrasound detector; dual sound time difference; dual sound pressure difference; volume reverberation; modeling and simulation*

1. INTRODUCTION

In the underwater detector, in order to improve anti-jamming ability, reduce the size of the transducer, usually use active ultrasonic detection signals, therefore, miniaturization ultrasonic devices which can quickly locate and identify an object become the key issue.

At present, underwater ultrasonic location algorithm can be divided into two categories: location algorithm based on beam-pointing and location algorithm based on geometric principles [1-3]. Beam-pointing location algorithm through time-shift of the signal collected, through shifting compensation time differences of the target to the sensor, the output of sensor array is obtained by average of the sum of compensation signal value, and the target location is the maximum output direction of sensor array. Location algorithm based on geometric principles primarily through the analysis of time difference that target reaches sensors array, and then target location based on the geometric relationship. These methods, due to that the effects of model assumptions cannot be processed on reverberation and direction noise, and did not meet the high sensitivity and fast response requirements of underwater detector in close range detection, high computational complexity, and sensor array size required, cannot be applied to the underwater detector of limit volume in the close range detection system.

In [4], location algorithm based on the sound pressure difference is proposed, according to the sound signal propagation, signal energy attenuation obeys the inverse square law, when the propagation distance of the signal reaches the sensor array is different, the received energy is also different, which can determine the target location. In this paper, combined with the time difference and pressure difference location algorithm, we put forward underwater close range detector dual sound location method, while the use of energy and time delay information, through the dual sound sensor can realize spatial location, can meet the detection requirements of underwater detector, and can reduce the size of array, suitable for volume required underwater detector.

The paper is organized as follows. In section 2, the mathematical model of dual sound location is proposed. In Section 3, Volume reverberation modeling is introduced. In Section 4, the simulation results illustrate the feasibility of the proposed dual

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sound location algorithm. In Section 5, we conclude the work of this paper.

2. DUAL SOUND LOCATION MODELING

According to the linear propagation characteristics of the sound wave, it can obtain the position and shape of the target in the space from the direction of propagation. Sound intensity can determine the position and shape of the target in the space. When the sound wave is reflected or scattered, the polarization state will change, and this change is associated with the reflecting surface or the geometric shape of the scattering body.

Underwater close range detector determines the target position, and generally only needs distance and azimuth. Underwater detector often adopts the active detection system, transmitting different waveform modulation signal to improve the detector resolution.

The emission signal using carrier amplitude controlled multi pulse modulation signal [5], namely a constant frequency (CF) pulse signal and triangular linear frequency modulated (LFM) pulse signal as signal source waveform of ultrasonic signal model, and the formula is

$$s(t) = \frac{1}{\sqrt{T}} rect(\frac{t}{T}) \exp(j2\pi f_i t) = \begin{cases} \exp(j2\pi f_i t) & 0 \le t \le \tau \\ 0 & t \ge \tau \end{cases} \quad (1)$$

Where τ is the signal modulation width, T is emission signal cycle, f_i is filled with high frequency pulse frequency. When $f_i=f_0$, transmits the CF signal; when the f_i $=f_0+K$ t transmits triangle LFM signal (f_0 is the starting frequency, K is the frequency offset constant).

Dual sound location uses the time difference or pressure difference of dual sensor signals to estimate the spatial position of the target. The time difference is obtained by correlation transform of received signals, such as time delay estimation method and relevant calculation method. Dual sensor signals not only have the time difference but also the pressure difference, sensor near the target has the higher pressure, it obtains pressure difference signal which plays the important role in the location. Through the time difference and the pressure difference signals of dual sensors, we can determine the location of the target.

L and R represent dual sound sensors. According to the inverse square law of the signal propagation, the received signal model of dual sensors can be expressed as:

$$s_L(t) = s(t)/d_L + \xi_L(t)$$
$$s_R(t) = s(t)/d_R + \xi_R(t)$$
(2)

Where $s(t)$ is the ultrasonic echo signal, $\xi_L(t)$ and $\xi_R(t)$ are the additive white noise. d_L and d_R are the distances between target and dual sensors.

In [4], the method of pressure difference location is proposed, and time delay information can be neglected in the energy calculation. There selected time range in the [0, T], the signal energy of L and R sound sensors are the square of time signal sampling as:

$$E_L = \int_0^T s_L^2(t)\mathrm{d}t = \frac{1}{{d_L}^2}\int_0^T s^2(t)\mathrm{d}t + \int_0^T \xi_L^2(t)\mathrm{d}t$$
$$E_R = \int_0^T s_R^2(t)\mathrm{d}t = \frac{1}{{d_R}^2}\int_0^T s^2(t)\mathrm{d}t + \int_0^T \xi_R^2(t)\mathrm{d}t$$
(3)

From Eq. (3), the energy and distance relationship as:

$$E_L d_L^2 = E_R d_R^2 + \eta$$
(4)

Where η is error, its expression as

$$\eta = \int_0^T [d_L^2 \xi_L^2(t) - d_R^2 \xi_R^2(t)]\mathrm{d}t$$

When the noise variance is small, error η can be approximated as zero.

Assumption (x_L,y_L), (x_R,y_R) and (x_S,y_S) are coordinates of dual sensors and the target, the distance from target to L and R dual sound sensors can be expressed as:

$$d_L = \sqrt{(x_L - x_S)^2 + (y_L - y_S)^2}$$
$$d_R = \sqrt{(x_R - x_S)^2 + (y_R - y_S)^2}$$
(5)

Substituting Eq. (5) into Eq. (4), the equation can be expressed as following:

$$E_L[(x_L - x_S)^2 + (y_L - y_S)^2]$$
$$= E_R[(x_R - x_S)^2 + (y_R - y_s)^2] + \eta$$
(6)

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Let

$$\gamma = E_L - E_R$$
$$\alpha = E_L x_L - E_R x_R$$
$$\beta = E_L y_L - E_R y_R$$
$$\psi = E_L(x_L^2 + y_L^2) - E_R\left(x_R^2 + y_R^2\right)$$

Eq. (6) can be transformed as:

$$(x_s \quad y_s \quad 1)\begin{pmatrix} \gamma & 0 & -\alpha \\ 0 & \gamma & -\beta \\ -\alpha & -\beta & \psi \end{pmatrix}\begin{pmatrix} x_s \\ y_s \\ 1 \end{pmatrix} = \eta$$

(7)

If $E_L \neq E_R$, Eq. (6) can be transformed as:

$$(x - \frac{\alpha}{\gamma})^2 + (y - \frac{\beta}{\gamma})^2 = \frac{E_L E_R d_{LR}^2}{\gamma^2} + \eta'$$

(8)

Where $d_{LR}^2 = (x_L - x_R)^2 + (y_L - y_R)^2$ is square of distance of dual sensors, $\eta' = \frac{\eta}{\gamma}$. From Eq. (8), the target is located on the circle, center is ($\frac{\alpha}{\gamma}, \frac{\beta}{\gamma}$), radius is $\sqrt{\frac{E_L E_R d_{LR}^2}{\gamma^2}}$ (ignoring the noise). In three-dimensional space, target can be determined in a ball.

If $E_L = E_R$, Eq. (6) can be expressed as:

$$2\alpha x_s + 2\beta y_s = \psi + \eta \qquad (9)$$

From Eq. (9), the target is located on the perpendicular bisector of dual sensors. If in three-dimensional space, the target location is on the vertical surface.

Through the above analysis, the pressure signal difference of dual sensors can determine the target location, but is unable to determine the specific location. In order to achieve the target orientation, it is necessary to combine with time difference signal.

In the time difference location of dual sensors, time difference τ_{LR} can be obtained by cross-correlation method [6]. The distance difference can be obtained by τ_{LR} multiplies by ultrasound velocity c, the equation as following:

$$\sqrt{(x_L - x_S)^2 + (y_L - y_S)^2} - \sqrt{(x_R - x_S)^2 + (y_R - y_S)^2} = c\tau_{LR}$$

(10)

Eq. (10) shows a curve as shown in Figure 1, this is a hyperbola, S is target, L and R are dual sound sensors.

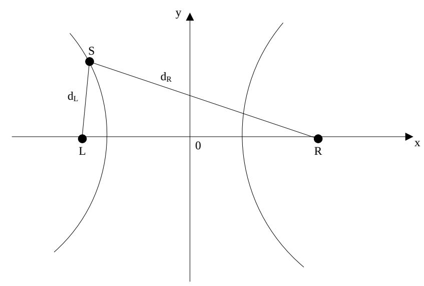

Figure 1: L and R Dual Sound Sensors Time Difference Signals Target Location

Simultaneous (6) and (10), the simplified equations as follows:

$$(x_L - x_S)^2 + (y_L - y_S)^2 = (r_L)^2$$
$$(x_R - x_s)^2 + (y_R - y_S)^2 = (r_R)^2$$

(11)

In Eq. (11), $r_L = |\frac{c\tau_{LR}}{1-\sqrt{\Delta E}}|, r_R = |\frac{c\tau_{LR}\sqrt{\Delta E}}{1-\sqrt{\Delta E}}|, \Delta E = E_L / E_R$.

From Eq. (11) structure, there are two round equations, centers are (x_L,y_L) and (x_R,y_R), radiuses are r_L and r_R. To determine the target location, two circles must have intersection, and meet the following distance conditions:

$$|r_L - r_R| \leq d_{LR} \leq r_L + r_R$$

(12)

Eq. (11) solution has the following two cases:

(a) When $\Delta E \neq 1$, that is $E_L \neq E_R$. Substituting r_L and r_R expressions into Eq. (12), the result as follow:

$$c|\tau_{LR}| \leq d_{LR} \leq c|\tau_{LR}|\left|\frac{1+\sqrt{\Delta E}}{1-\sqrt{\Delta E}}\right|$$

In the triangle formed by dual sensors and target, $|d_L - d_R| \leq d_{LR}$ and $d_{LR} \leq |d_L + d_R|$, therefore, the two inequalities $0 \leq c|\tau_{LR}| \leq d_{LR}$ and $d_{LR} \leq c|\tau_{LR}|\left|\frac{1+\sqrt{\Delta E}}{1-\sqrt{\Delta E}}\right|$ are established, Eq. (12) meet the conditions has solutions.

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(b) When $\Delta E = 1$, that is $E_L = E_R$. Where $c|\tau_{LR}| = 0$ target located on the perpendicular bisector of dual sound sensors, it can not determine the specific location by Eq. (12). To resolve this problem, dual sensors array can be rotated angle, problem solving becomes the first case (a), proposed location method is still valid.

For real time calculation of target azimuth, there gives analytic solutions in real-time computing. Eq. (11) can be expanded as:

$$\begin{cases} x_L{}^2 - 2x_L x_S + x_S{}^2 + y_L{}^2 - 2y_L y_s + y_s{}^2 = r_L{}^2 \\ x_R{}^2 - 2x_R x_s + x_S{}^2 + y_R{}^2 - 2y_R y_S + y_S{}^2 = r_R{}^2 \end{cases}$$

(13)

Let

$$R_L{}^2 = x_L{}^2 + y_L{}^2, R_R{}^2 = x_R{}^2 + y_R{}^2, R_S{}^2 = x_S{}^2 + y_S{}^2$$

Then Eq. (13) can be transformed as:

$$\begin{cases} R_L{}^2 + R_s{}^2 - 2x_L x_S - 2y_L y_s = r_L{}^2 \\ R_R{}^2 + R_S{}^2 - 2x_R x_s - 2y_R y_s = r_R{}^2 \end{cases}$$

(14)

Solving Eq. (14), x_S, y_S as following:

$$a = 2x_L y_R - 2x_R y_L, b = r_R{}^2 - R_R{}^2, e = R_L{}^2 - r_L{}^2,$$

Let $f = y_R - y_L, g = x_R - x_L$

Then Eq. (14) can be transformed as:

$$\begin{cases} x_S = \dfrac{by_L + ey_R + R_S{}^2 f}{a} \\ y_S = -\dfrac{bx_L + ex_R + R_S{}^2 g}{a} \end{cases}$$

(15)

Substituting Eq. (15) into $R_S{}^2 = x_S{}^2 + y_S{}^2$, it can be expressed as

$$(f^2 + g^2)R_S{}^4 + (2bfy_L + 2efy_R + 2bgx_L + 2egx_R - a^2)R_S{}^2 +$$
$$(by_{L:} + ey_R)^2 + (bx_L + ex_R)^2 = 0$$

(16)

Solving $R_S{}^2$ into Eq. (15), it can be solved target location coordinates, Eq. (16) can be seen as a quadratic equation, the solutions as follows:

$$\begin{cases} x_{S1} = \dfrac{by_L + ey_R}{a} - \dfrac{(by_L + ey_R + bx_L + ex_R) f^2}{a(f^2 + g^2)} + \\ \dfrac{f\sqrt{(by_L + ey_R + bx_L + ex_R)^2 f^2 - (f^2 + g^2)((by_L + ey_R)^2 + (bx_L + ex_R)^2 - a^2 R_S{}^2)}}{a(f^2 + g^2)} \\ y_{S1} = -\dfrac{bx_L + ex_R}{a} + \dfrac{gby_L + ey_R + bx_L + ex_R) f}{a(f^2 + g^2)} - \\ \dfrac{\sqrt{(by_L + ey_R + bx_L + ex_R)^2 f^2 - (f^2 + g^2)((by_L + ey_R)^2 + (bx_L + ex_R)^2 - a^2 R_S{}^2)}}{a(f^2 + g^2)} \end{cases}$$

$$\begin{cases} x_{S2} = \dfrac{by_L + ey_R}{a} - \dfrac{(by_L + ey_R + bx_L + ex_R) f^2}{a(f^2 + g^2)} - \\ \dfrac{f\sqrt{(by_L + ey_R + bx_L + ex_R)^2 f^2 - (f^2 + g^2)((by_L + ey_R)^2 + (bx_L + ex_R)^2 - a^2 R_S{}^2)}}{a(f^2 + g^2)} \\ y_{S2} = -\dfrac{bx_L + ex_R}{a} + \dfrac{gby_L + ey_R + bx_L + ex_R) f}{a(f^2 + g^2)} + \\ \dfrac{\sqrt{(by_L + ey_R + bx_L + ex_R)^2 f^2 - (f^2 + g^2)((by_L + ey_R)^2 + (bx_L + ex_R)^2 - a^2 R_S{}^2)}}{a(f^2 + g^2)} \end{cases}$$

(17)

3. VOLUME REVERBERATION MODELING

In underwater ultrasonic detection, volume reverberation is the main interference. The traditional volume reverberation theory mainly considers the remote detection, but this paper mainly studies close range detection. Therefore, the paper makes approximate processing according to traditional volume reverberation theory analysis method [7-10]. Coordinate system is established as shown in figure 2.

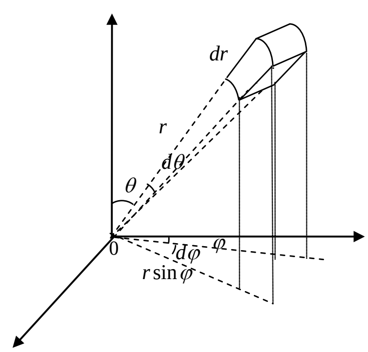

Figure 2: Scattering Unit Coordinate System

According to the coordinate system, volume reverberation model as follows:

$$I_{ro}(\theta, \varphi) = I_{rm} D^2(\theta, \varphi)$$

(18)

Where $D^2(\theta, \varphi)$ is sound sensor directivity; θ is the angle of direction vector and Z axis, φ is the angle of projection in XOY plane and X axis; $I_{ro}(\theta, \varphi)$ is sound intensity where the distance is r with target on (θ, φ) direction.

From sound source at *r*, the scattering power *W* of per unit volume (*dV*) can be expressed as:

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$$W = I_{ro}(\theta,\varphi)\alpha_v$$
(19)

Where α_v is volume scattering coefficient, $dI_s(\theta,\varphi)$ is the sound intensity of dV scattering, the reverberant sound intensity of the dual sound sensors as:

$$dI_s = \frac{WdV}{4\pi r^2} D^2(\theta,\varphi) e^{-2\alpha r}$$
(20)

Where α is marine medium absorption coefficient. Substituting Eq. (18) into Eq. (20) that

$$\begin{cases} dI_s = \dfrac{I_{rm}\alpha_v}{4\pi r^2} D^4(\theta,\varphi) dV e^{-2\alpha r} \\ I_{rm} = \dfrac{W\gamma}{4\pi r^2} e^{-2\beta r} \end{cases}$$
(21)

Where γ is clustering coefficient, and its value is:

$$\gamma = \frac{4\pi}{\int_0^{2\pi} d\varphi \int_0^{\pi} R^2(\theta,\varphi)\sin\theta d\theta}$$
(22)

Eq. (22) integral that

$$I_s = \int dI_s = \frac{W\alpha_v\gamma}{(4\pi)^2}\int \frac{e^{-4\alpha r}}{r^4} D^4(\theta,\varphi) dV$$
(23)

In Figure 2 coordinate system, scattering body unit dV can be expressed as:

$$dV = r^2 \sin\theta d\theta dr$$

Let the speed of sound in water is C, sound pulse width is τ, and volume reverberation intensity at r can be expressed as

$$I_s = \frac{W\alpha_v\gamma}{(4\pi)^2}\int_0^{2\pi} d\varphi \int_0^{\pi} D^4(\theta,\varphi)\sin\theta d\theta \int_{r_d}^{r_d+\frac{\tau c}{2}} \frac{e^{-4ar}}{r^2} dr$$
$$= \frac{W\alpha_v\gamma}{4\pi} \frac{\int_0^{2\pi} d\varphi \int_0^{\pi} D^4(\theta,\varphi)\sin\theta d\theta}{\int_0^{2\pi} d\varphi \int_0^{\pi} D^2(\theta,\varphi)\sin\theta d\theta} \int_{r_d}^{r_d+\frac{\tau c}{2}} \frac{e^{-4ar}}{r^2} dr$$
(24)

$$D_v = \frac{\int_0^{2\pi} d\varphi \int_0^{\pi} R^4(\theta,\varphi)\sin\theta d\theta}{\int_0^{2\pi} d\varphi \int_0^{\pi} R^2(\theta,\varphi)\sin\theta d\theta}$$
(25)

Substituting (25) into (24):

$$I_s = \frac{W\alpha_v V_v}{4\pi}\int_{r_d}^{r_d+\frac{\tau c}{2}} \frac{e^{-4ar}}{r^2} dr$$
(26)

Eq. (26) solution as:

$$I_s = \frac{W\alpha_v d_v \tau c e^{-4ar_d}}{8\pi r_d^2}$$
(27)

4. SIMULATION RESULTS AND ANALYSIS

The measured conductance and susceptance curves of dual sound sensors are shown in Figure 3 and Figure 4 , the frequency of the selected filled sine pulse signal is 525kHz , the signal period T=2.5ms, where the signal detection time width = 1ms , delay time = 1.5ms.

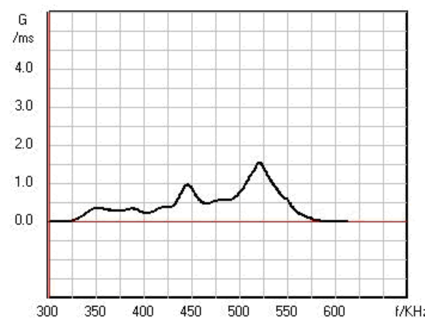

Figure 3: Conductance Curve

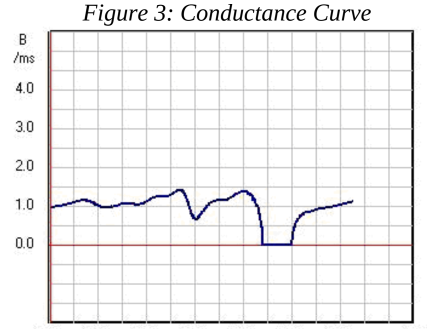

Figure4: Susceptance Curve

To simplify the analysis , assuming the received signals of dual sound sensors that meet the following conditions : (1) the target does not cause signal distortion ; (2) there is no secondary scattering ; (3) water medium is uniformly unlimited; (4)without taking into account the transmission loss ; (5) the origin is a corner of the simulation pool, three pool surfaces are axis (unit: meter).Target coordinate is (1, 3, 1.5), dual sensor coordinates are (2, 2, 1.5) ,(4, 2, 1.5).

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4.1 Location Simulation with No Reverberation

Simulation results as shown in Figure 5. It can be seen from the diagram, two circles there are two intersections, and this is because of the mirror fuzzy phenomena of the linear array. To solve this problem, dual sensors is rotated 90 °, the proposed algorithm is used again, and the location of the target can be determined by twice location.

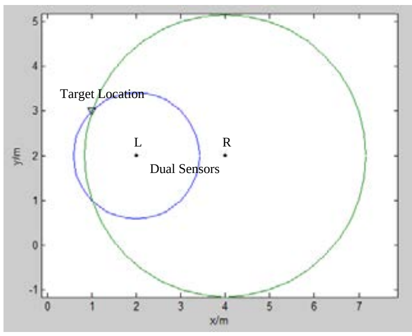
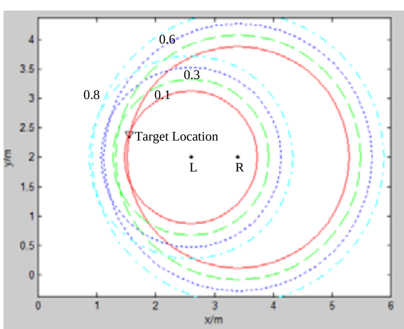


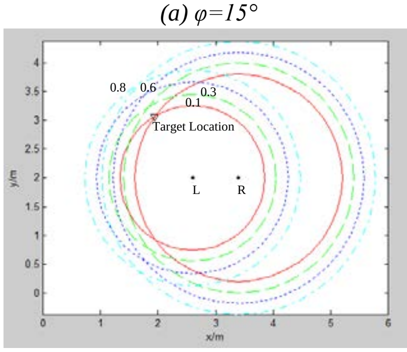
Figure.5: Joint Location under No Reverberation

4.2 Location Simulation with Volume Reverberation

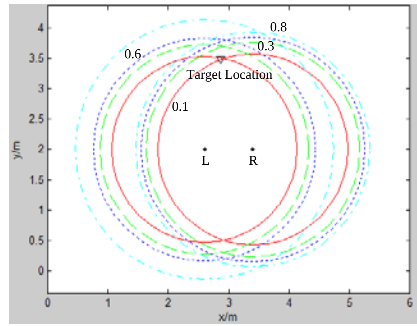
There considering volume scattering coefficient of reverberation effects, the coordinates of dual sensors are (2.6,2,1.5) and (3.4,2,1.5), target moving along φ=15°, 45°, 85° direction at 1.5m from the array Centre. Volume scattering coefficient (α_v) respectively 0.1, 0.3, 0.6, 0.8, the simulation results as shown in Figure 6.



(a) φ=15°



(b) φ=45°



(c) φ=85°

Figure 6: Different Location Of The Target Under Reverberation

Root mean square error is calculated in different directions and different scattering volume coefficients, the formula as follows:

$$rmse = \frac{1}{n}\sum_{j=1}^{n}\sqrt{(\hat{x}_j - x_s)^2 + (\hat{y}_j - y_s)^2} \tag{28}$$

Where n is the number of repeat test, $(\hat{x}_j, \hat{y}_j)$ is the j-th location result, error analysis is shown in Table 1.

Table 1: Error Analysis in Different Orientations and Different Scattering Volume Coefficients

rmse α_v / φ	0.1	0.3	0.6	0.8
15°	0.01	0.12	0.16	0.70
45°	0.02	0.06	0.18	0.82
85°	0.04	0.23	0.30	1.35

The simulation results show that the proposed dual sound location algorithm that joint pressure difference and time difference signal, in the lower reverberation conditions can quickly determine the target, its location accuracy associates with the target's orientation. When the normal angle of the target and dual sensors array tends to 0, because the received energy between two sensors is very near, ΔE close to 1, if the reverberation is larger, the signal energy by error impact will be larger, small error may make the energy ratio changed from ΔE >1 to <1, the location result will be inaccurate. In order to improve the location precision and reliability, received signals need to be a more detailed analysis.

5. CONCLUSION

This paper mainly studies the underwater ultrasonic detector dual sound location technology, in order to have the ability of fast target location. By the analysis of pressure difference location

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model and time difference location model, the dual sound location algorithm of joint pressure difference with time difference signal is proposed, and derives the analytic solution for real-time location. Linear array mirror fuzzy problem can be solved by second location with rotating dual sensors 90°. The problem that the target is unable to location when it is located in perpendicular bisector is solved by dual sensors rotating angle. Underwater volume reverberation model is established. Simulation results show that the algorithm under low reverberation conditions can obtain a good location effect. Under large reverberation, in order to improve the location precision and reliability, received signals need to be a more detailed analysis.

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