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A GPS Positioning Method for Underwater Targets Using Dual Acoustic Devices

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Abstract

Since the existing underwater GPS positioning technology can only position underwater targets equipped with acoustic transponders, this study proposed a method of positioning underwater combining targets based on an ultra short baseline forward-looking sonar acoustic device. The mathematical model of the obtaining longitude and latitude coordinates of the underwater target in the WGS84 ellipsoidal coordinate system was established. A group of data was given based on the measuring state, and Monte Carlo simulation was carried out to study the effects of the random errors in the indirect measurements in the algorithm on the positioning accuracy and the combined effect of the random errors in the indirect measurements in the algorithm on the positioning accuracy at different geological locations. The preset target was measured in the offshore waters of Dalian, confirming the validity of the proposed algorithm.

***Keywords**: Underwater GPS, Acoustic positioning, Ultra short baseline, Forward-looking sonar*

1. Introduction

Currently, the location-based service and time service of the global positioning system (GPS) are facilitating people"s production and life in various global fields. However, GPS is not genuinely global, and it has two blind areas: First of all, because the clock used by a user receiver and the clock borne by a satellite are unlikely to be always synchronous, in addition to the three-dimensional coordinates of the user, it is also necessary to introduce an unknown time quantum; therefore, the location to be positioned is required to be able to receive four satellite signals; second, the devices in GPS communicate via electromagnetic waves, which are a kind of radiated wave that can propagate in the air and in a vacuum and can attenuate quickly in water.

Positioning and navigation are closely related. Navigation is continuous positioning, and underwater positioning originates in military navigation [1]. Existing underwater navigation and positioning methods primarily include dead reckoning and inertial navigation, geophysical navigation, simultaneous localization and mapping, and underwater acoustic positioning systems, etc. [2-5], and underwater acoustic positioning systems are not only used for navigation, but also for the exploration and development of marine mineral resources, construction, underwater archaeology, and rescue and salvage, etc [6-8]. Based on the length of the baseline for the placed acoustic array, underwater acoustic positioning systems can be divided into long baseline positioning systems, short baseline positioning systems, and ultra short baseline positioning systems [9-11]. The acoustic array of a long baseline positioning system is placed at the bottom or on the surface of a sea with a wide positioning range, but the measurement, placement, and recovery of the array are complex. The acoustic array of a short baseline positioning

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system is placed at the bottom of a mother ship. Due to the limited length of the baseline and because the increase in the operating range can easily cause range ambiguity, its positioning range and depth are smaller than that those of a long baseline operating system. The baseline length of an ultra short baseline positioning system is smaller than half of a wavelength, and the acoustic array is encapsulated and placed at the bottom of a mother ship. Because the reception in a far field, namely the fact that the sound rays incident on all primitives is parallel, is based on to realize positioning, the positioning accuracy is relatively high only in a limited cone below the array. In recent years, with the development of the ranging and direction-fining techniques of acoustic systems, ultra short baselines have improved in the operating range, operating depth and positioning accuracy and have been increasingly used additionally due to their convenient and flexible operation.

An underwater GPS is primarily a combination of a GPS and an acoustic positioning system and consists of two types [12-19]: a sea surface buoy system using a long baseline and carrying a GPS receiver, which can track, monitor, and dynamically position underwater targets from a sea surface, coastal land, and a plane and has a large operating range but can only position underwater targets that carry acoustic transponders in certain waters; and a system which uses a mother ship equipped with a short baseline or ultra short baseline transceiver and a GPS receiver, which is mobile and flexible but also can only position targets equipped with acoustic transponders. Therefore, this paper proposes a way of positioning combining an ultra short baseline, a forward-looking sonar and a GPS receiver, overcoming the limitation of the existing underwater GPS positioning technology that it can only position targets equipped with acoustic transponders and realizing the real-time positioning of the longitude and latitude coordinates of any unknown targets in any waters in the WGS84 ellipsoidal coordinate system, and it is also highly mobile.

2. Method

2.1. Positioning Principle

The underwater GPS positioning method based on dual acoustic devices uses an ultra short baselin ultra short baseline (USBL) and a forward-looking sonar (FLS) to extend GPS positioning underwater. As shown in Figure 1, the mother ship is equipped with a differential GPS mobile station; a forward-looking sonar is installed at the front end of the remote operated vehicle (ROV), and an ultra short baseline transceiver and an ultra short baseline transponder are placed at the bottom of the mother ship and in the ROV respectively. The ultra short baseline can be used together with the differential GPS and other auxiliary equipment to obtain the longitude and latitude coordinates of the ultra short baseline transponder carried by the ROV in the WGS84 ellipsoidal coordinate system, and the imaging of a target in the forward-looking sonar and the relative positions of the forward-looking sonar and the ultra short baseline transponder can be to obtain the variations of the target relative to the longitude and latitude coordinates of the ultra short baseline transponder. The longitude and latitude coordinates of the target in the WGS84 ellipsoidal coordinate system can be obtained by adding the two results.

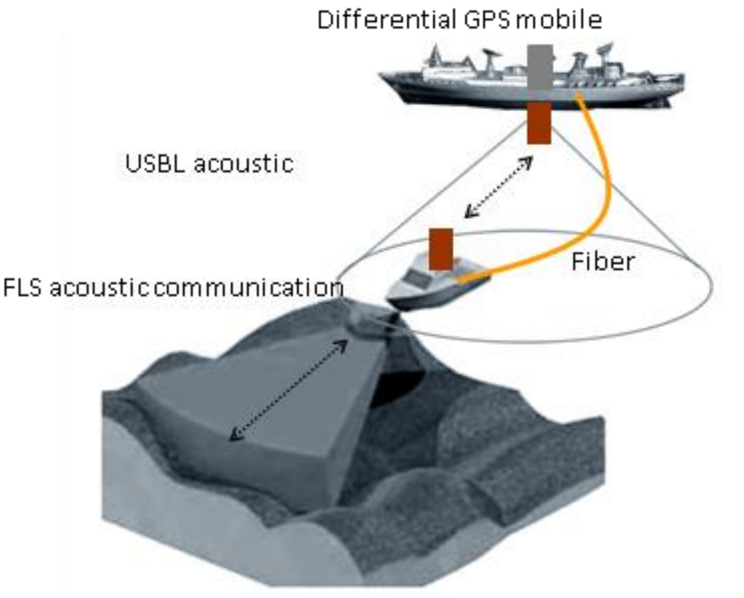


Figure 1. The Schematic Diagram of GPS Positioning for the Underwater Target Using Double Acoustic Device

The underwater GPS positioning method based on dual acoustic devices uses an ultra short baselin ultra short baseline (USBL) and a forward-looking sonar (FLS) to extend GPS positioning underwater. As shown in Figure 1, the mother ship is equipped with a differential GPS mobile station; a forward-looking sonar is installed at the front end of the remote operated vehicle (ROV), and an ultra short baseline transceiver and an ultra short baseline transponder are placed at the bottom of the mother ship and in the ROV respectively. The ultra short baseline can be used together with the differential GPS and other auxiliary equipment to obtain the longitude and latitude coordinates of the ultra short baseline transponder carried by the ROV in the WGS84 ellipsoidal coordinate system, and the imaging of a target in the forward-looking sonar and the relative positions of the forward-looking sonar and the ultra short baseline transponder can be to obtain the variations of the target relative to the longitude and latitude coordinates of the ultra short baseline transponder. The longitude and latitude coordinates of the target in the WGS84 ellipsoidal coordinate system can be obtained by adding the two results.

2.2. Establishment of Coordinate Systems

In order to obtain the longitude and latitude coordinates of an underwater target in the WGS84 ellipsoidal coordinate system, the following coordinate systems were required to be established: (1) a North East Down topocentric horizontal rectangular coordinate system $O_bx_by_bz_b$, where the center of the transducer of the ultra short baseline transponder is the origin O_b; the straight line tangent to the longitude passing through O_b is the x_b axis, positive northward; the straight line tangent to the latitude passing through O_b is the y_b axis, positive eastward; and the z_b, x_b, and y_b axes constitute a right-handed coordinate system; (2) A forward-looking sonar coordinate system $O_sx_sy_sz_s$, where the center of the head of the forward-looking sonar is the origin O_s; the direction passing through O_s along the forward-looking sonar is the positive direction of the x_s axis; the intersection of the plane perpendicular to O_sx_s passing through O_s and the cross section of the forward-looking sonar passing through O_s is the y_s axis, positive to the right along the forward-looking sonar; the z_s, x_s, and y_s axes constitute a right-handed coordinate system; (3) A ROV coordinate system $O_rx_ry_rz_r$, where the origin O_r overlaps with the origin O_s of the forward-looking sonar coordinate system; the y_r axis overlaps with the y_s axis of the forward-looking sonar coordinate system; the x_r axis is the axis of the ROV passing through O_r, positive forward; and the z_r, x_r, and y_r axes constitute a right-handed coordinate system.

2.3. Calculation of Longitude and Latitude Coordinates

The longitude and latitude coordinates (*lon*1, *lat*1) of the ultra short baseline transponder fixed on the ROV in the WGS84 ellipsoidal coordinate system were output in real time by the Tracklink software included in the ultra short baseline positioning system based on the data collected in real time by the ultra short baseline positioning system, the shipborne differential GPS mobile station, the shipborne compass, and the shipborne attitude sensor, the predetermined initial offset in the installation of the shipborne differential GPS mobile station, the shipborne compass, and the shipborne attitude sensor, and the sound velocity in the current waters. The variations (△*lon*, △*lat*) of the target relative to the longitude and latitude coordinates of the ultra short baseline transponder on the ROV in the WGS84 ellipsoidal coordinate system were obtained by taking the following steps:

(1) The coordinates of the underwater target in the forward-looking sonar coordinate system $O_s x_s y_s z_s$ are:

$$\begin{aligned} x_s &= l \cdot \cos\theta \\ y_s &= l \cdot \sin\theta \\ z_s &= z \end{aligned} \tag{1}$$

where l and θ are the slant distance and bearing angle between the target and the head of the forward-looking sonar, and z is the vertical distance between the target and the coordinate plane $O_s x_s y_s$, both of which are given by the forward-looking sonar.

(2) The coordinates of the underwater target in the ROV coordinate system $O_r x_r y_r z_r$ are:

$$\begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} = \begin{bmatrix} \cos\eta & 0 & -\sin\eta \\ 0 & 1 & 0 \\ \sin\eta & 0 & \cos\eta \end{bmatrix} \cdot \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} \tag{2}$$

where η is the tilt angle of the forward-looking sonar relative to the horizontal plane.

(3) The coordinates of the underwater target in the North East Down topocentric horizontal rectangular coordinate system are:

$$\begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} = R_{rb} \cdot \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} - R_{rb} \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} \tag{3}$$

where x_0, y_0, and z_0 are the coordinates of the three-dimensional positions of the center of the transducer of the ultra short baseline transponder in the ROV coordinate system. The expression for R_{rb} is as follows:

$$R_{rb} = \begin{bmatrix} \cos\gamma\cos\alpha - \sin\gamma\sin\beta\sin\alpha & \cos\gamma\sin\alpha + \sin\gamma\sin\beta\cos\alpha & -\sin\gamma\cos\beta \\ -\cos\beta\sin\alpha & \cos\beta\cos\alpha & \sin\beta \\ \sin\gamma\cos\alpha + \cos\gamma\sin\beta\sin\alpha & \sin\gamma\sin\alpha - \cos\gamma\sin\beta\cos\alpha & \cos\gamma\cos\beta \end{bmatrix}$$

where α is the yaw angle of the forward direction of the ROV relative to the north and is given by the gyrocompass on the ROV; β is the roll angle of the ROV, and γ is the pitch angle of the ROV, both of which are given by the attitude sensor on the ROV.

(4) As shown in Figure 2, the quarter ellipsoidal cap is the ellipsoidal cap of the WGS84′ellipsoid passing through the center O_b of the transducer of the ultra short baseline transponder, concentric with the WGS84 ellipsoid, and parallel with the ellipsoidal surface; m is the intersection of the plumb line passing through the measuring point of the underwater target and the ellipsoidal cap of the WGS84′ ellipsoid; m' is the intersection of mm' and the coordinate plane $O_b x_b y_b$, and mm' is parallel with OO_b. Therefore, the variations (Δlon, Δlat) of the underwater target relative to the longitude and latitude coordinates of the ultra short baseline transponder fixed on the ROV in the WGS84 ellipsoidal coordinate system are,

$$\Delta lon = \frac{360}{\pi} \cdot \arctan(\frac{y_b}{2 \cdot (N - H + \xi) \cdot \cos(lat1)}) \tag{4}$$

$$\Delta lat = \frac{360}{\pi} \cdot \arctan(\frac{x_b}{2 \cdot (N - H + \xi)}) \tag{5}$$

where $lat1$ is the coordinate of the latitude of the center of the transducer of the ultra short baseline transponder in the WGS84 ellipsoidal coordinate system; ξ is the quasi-geoid height anomaly at the location of the ultra short baseline transponder and can be read using the quasi-geoid height anomaly map of the WGS84; H is the normal height at the location of the ultra short baseline transponder and is the sum of the z coordinate of the ultra short baseline transponder in the transceiver coordinate system and the depth of the transceiver in the water (the former is negative because the transponder is below sea level when operating); N is the radius of curvature in prime vertical at the projection of the plumb line passing through the ultra short baseline transponder on the WGS84 ellipsoid and is expressed as [20],

$$N = \frac{a}{\sqrt{1 - \frac{(a^2 - b^2)}{a^2} \cdot (\sin(lat1))^2}} \tag{6}$$

where a and b are the major semi-axis and minor semi-axis of the WGS84 ellipsoid. Therefore, the measured values (lon, lat) of the longitude and latitude of the underwater target in the WGS84 ellipsoidal coordinate system are

$$lon = lon1 + \Delta lon \tag{7}$$

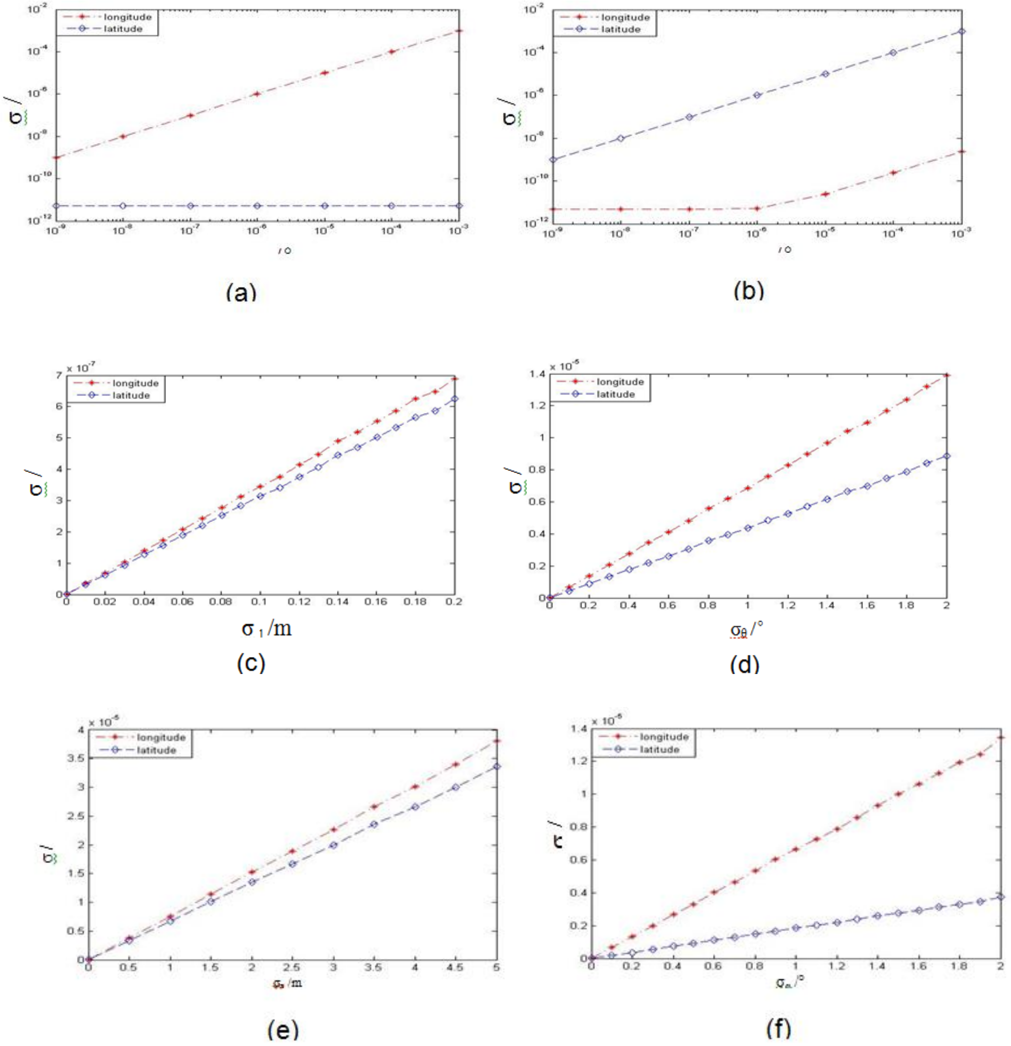
$$lat = lat1 + \Delta lat \tag{8}$$

3. Results and Discussion

3.1. Uncertainty Analysis of Positioning Accuracy Based on Monte Carlo

Monte Carlo, a method of solving problems using random numbers based on theories about probability statistics, was used to study the effects of the random errors in the indirect measurements in the algorithm on the accuracy of positioning the underground target. In order to approximate to actual conditions and facilitate analysis and calculation, the following assumptions were made: (a) The measured variables are independent of one another; (b) The measured variables obey normal distributions. a=6378138;

b=6356752.29821597; ξ=0; η=45°; x_0=-1; y_0=0.3 and z_0=-0.6. A group of variables in a measuring state were randomly taken: $lat1$=38.87253889°, $lon1$=121.67832456°, l=50m, θ=20°, z=0m, $\alpha=\beta=\gamma$=30° and H=30.7m. The relationships between the positioning accuracy and the uncertainties of the variables are shown in Figure 3. It can be seen that: (1) According to Figure 3(a), the uncertainty of the longitude at the location of the ultra short baseline transponder produced no effect on the uncertainty of the positioning of the latitude of the underwater target; (2) According to Figure 3(b), the uncertainty of the latitude at the location of the ultra short baseline transponder presented a linear relationship with the uncertainty of the positioning of the longitude of the underwater target after being greater than a certain value; (3) According to Figure 3(h), The uncertainty of the pitch angle of the ROV had no effect on the uncertainty of the positioning of the longitude of the underwater target; (4) In Figure 3, other variables showed linear relationship with the uncertainty of the positioning of the longitude and latitude of the underwater target; (5) According to Figure 3(e), when permitted by accuracy requirement, a two-dimensional forward-looking sonar can be used to position the underwater target, and when the opening angle of the beam in its vertical direction was fixed, the closer the forward-looking sonar was to the target, the higher the positioning accuracy was; (6) The uncertainty of the positioning of the ultra short baseline is the major factor affecting the accuracy of the positioning of the underwater target, and the uncertainties of the normal height at the location of the transponder has insignificant effects on the positioning accuracy.



(a) (b)

(c) (d)

(e) (f)

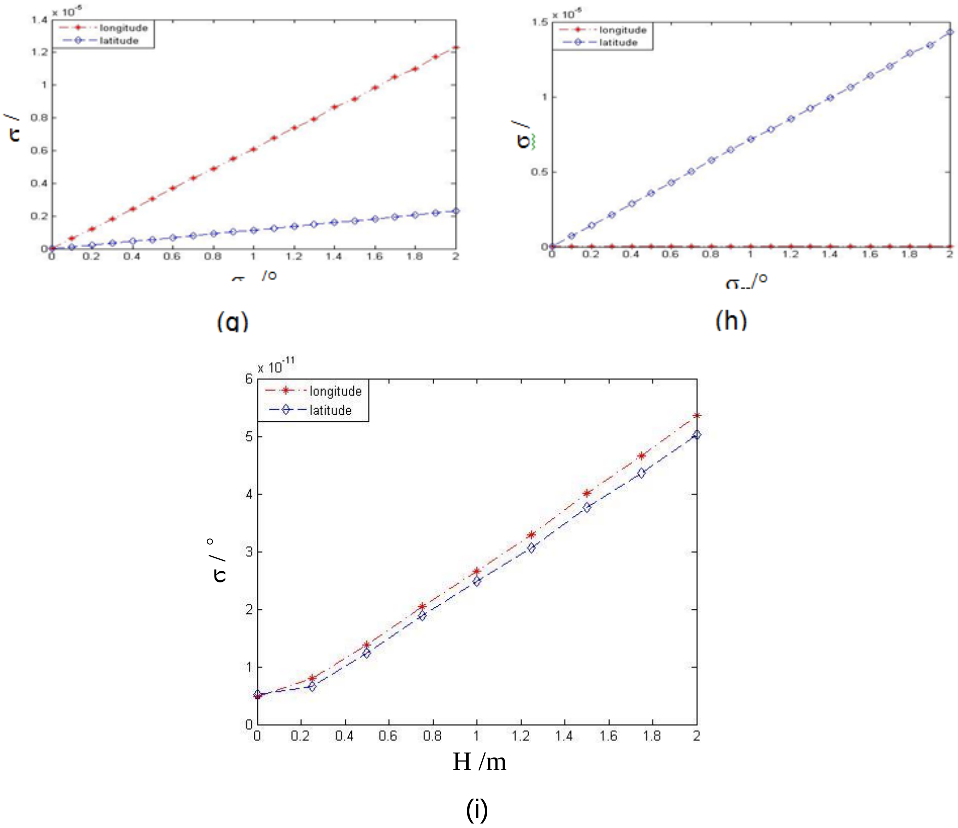
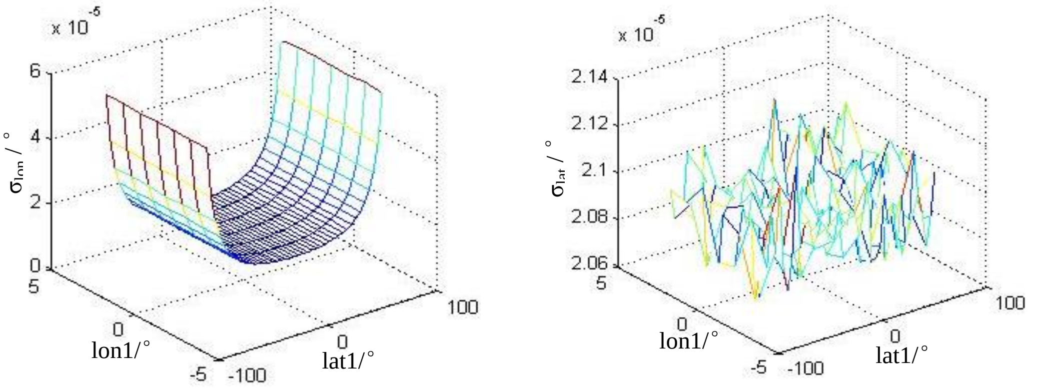


Figure 3. The Influence of the Uncertainty of the Indirect Measurements in the Algorithm on the Positioning Accuracy for the Underwater Target

(a) The Influence of Uncertainty of the USBL Transponder Longitude on the Positioning Accuracy. (b) The Influence of Uncertainty of the USBL Transponder Latitude on the Positioning Accuracy. (c) The Influence of Uncertainty of the FSL Slant Range on the Positioning Accuracy. (d) The Influence of Uncertainty of the FSL Bearing Angle on the Positioning Accuracy. (e) The Influence of Uncertainty of the Vertical Distance between the Target and the Coordinate Plane Osxsys on the Positioning Accuracy. (f) The Influence of Uncertainty of the ROV Yaw Angle on the Positioning Accuracy. (g) The Influence of Uncertainty of the ROV Roll Angle on the Positioning Accuracy. (h) The Influence of Uncertainty of the ROV Pitch Angle on the Positioning Accuracy. (i) The Influence of Uncertainty of Normal High at the Location of USBL Transponder on the Positioning Accuracy

Similarly based on the above given parameters, the above variables (except lat1 and lon1) were averaged. Based on the accuracies of the measuring devices, the corresponding uncertainties were σ_{lat1}=0.000019°, σ_{lon1}=0.000012°, σ_{l}=0.05m, σ_{θ}=1°, σ_{z}=1m, σ_{α}=1°, $\sigma_{\beta}=\sigma_{\gamma}$=0.4°, and σ_{H}=1m, respectively. The random number was given according to the normal distribution. Then the equation solving was carried out using the above method. After 15,000 repetitions were performed, the uncertainty of the positioning of the longitude and latitude of the underwater target in the *lat*1 (-80°<*lat*1<80°, a step size of 4°), lon1 (-3°<*lon*1<3°, a step size of 1°) six-degree zone was obtained and is shown in Figure 4, and the extreme value is shown in Table 1. It can be seen that: (1) the uncertainty of the positioning of the longitude of the underwater target increased as the latitude increased; and (2) the uncertainty of the positioning of the latitude of the underwater target was unrelated to the geological location, which was related to the solution expression and was a reflection of the error transfer coefficient.



(a) (b)

Figure 4. The Influence of the Uncertainty of the Indirect Measurements in the Algorithm on the Positioning Accuracy of the Underwater Target at Different Geographic Location of USBL Transponder

(a) The Influence of Uncertainty of the Indirect Measurements in the Algorithm on the Positioning of the Longitude at the Different Geological Location. (b) The Influence of Uncertainty of the Indirect Measurements in the Algorithm on the Positioning of the Longitude at the Different Geological Location

Table1. The Extreme Value of Positioning Accuracy of the Underwater Target at Different Geographic Position of USBL Transponder

max(σ_{lon})	min(σ_{lon})	max(σ_{lat})	min(σ_{lat})
0.0000574°	0.0000155°	0.0000213°	0.0000207°
4.73m	1.34m	2.38m	2.31m

3.2. Error Validation through Marine Measurement

An underwater target was preset in offshore waters of Dalian. The longitude and latitude coordinates (*lonz*, *latz*) of this target were obtained by the shipborne differential GPS before it entered the water, as the true values of the coordinates at the location of the target. A mother ship stopped at a certain distance from the waters where the target was located. The ROV entered the water from the mother ship, and the GSP positioning system featuring dual acoustic devices was used to measure the longitude and latitude coordinates (*lon*, *lat*) of the target in the WGS84 ellipsoidal coordinate system. Commercial coordinate conversion software was used to convert the above two groups of coordinates (*lonz*, *latz*) and (*lon*, *lat*) into the two-dimensional coordinates (x_z, y_z) and (x, y) in the projected geodetic rectangular plane coordinate system 3-degree Gauss-Kruger zone. The positioning error in the underwater target is defined as follows:

$$\Delta d = \sqrt{(x - x_z)^2 + (y - y_z)^2} \tag{9}$$

Table 2. Experimental Data

Group number	Position of the transponde		Measured values of the target				True values of the target				Positioning error
	lon1	lat1	lon	lat	x_c	y_c	lonz	latz	x_z	y_z	$\|\Delta d\|$
1	121° 40′ 42.03″	38° 52′ 20.94″	121° 40′ 41.00″	38° 52′ 21.10″	4305183.040 m	385277.378 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	1.22m
2	121° 40′ 42.01″	38° 52′ 20.91″	121° 40′ 41.12″	38° 52′ 21.20″	4305185.992 m	385280.257 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	3.03m
3	121° 40′ 41.98″	38° 52′ 20.93″	121° 40′ 40.95″	38° 52′ 21.09″	4305182.592 m	385276.129 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	2.33m
4	121° 40′ 41.95″	38° 52′ 20.95″	121° 40′ 40.97″	38° 52′ 21.21″	4305186.372 m	385276.687 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	2.50m
5	121° 40′ 41.92″	38° 52′ 20.92″	121° 40′ 41.04″	38° 52′ 21.02″	4305180.414 m	385278.340 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	3.78m
6	121° 40′ 41.87″	38° 52′ 20.97″	121° 40′ 41.12″	38° 52′ 21.08″	4305182.492 m	385280.247 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	2.92m
7	121° 40′ 41.83″	38° 52′ 20.91″	121° 40′ 40.91″	38° 52′ 21.01″	4305180.204 m	385275.164 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	4.78m
8	121° 40′ 41.81″	38° 52′ 20.93″	121° 40′ 41.07″	38° 52′ 21.04″	4305181.142 m	385278.917 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	3.20m
9	121° 40′ 41.79″	38° 52′ 20.90″	121° 40′ 40.91″	38° 52′ 20.97″	4305178.976 m	385275.161 m	121° 40′ 41.02″	38° 52′ 21.14″	4305184.162 m	385277.847 m	2.92m

$\bar{x} = 2.96m$

$1\sigma = 0.98m$

Several groups of measured data are shown in Table 2: (1) The average error was 2.96 m and was a combined reflection of the error in the measuring principle, the error in installation calibration, and errors in the equipment; (2) When a normal distribution was used to represent the random error in positioning, the 1σ uncertainty was 0.98m. Because it was in offshore areas, the ultra short baseline always operated within a taper angle of 60°, and the forward-looking sonar was not distant from the target, the two key acoustic devices in the measuring system the ultra short baseline and the forward-looking sonar maintained high measuring accuracies.

4. Conclusions

It is appropriate for the existing underwater long baseline GPS positioning method to be used to construct global marine stereo positioning systems and guide people to engage in constructive work such as underwater construction and surveying of submarine energy. It is more appropriate for the ultra short baseline forward-looking sonar positioning method introduced in this paper to be used to guide people to engage in exploratory work such as underwater archaeology and rescue and salvage, especially today when marine stereo positioning systems are not global.

The underwater GPS positioning method based on dual acoustic devices made use of acoustic positioning to extend GPS positioning underwater, so it was constrained by the accuracies of acoustic positioning devices and other auxiliary devices and had a lower positioning accuracy than a GPS. Monte Carlo simulation was carried out to study the effects of the random errors in the indirect measurements in the positioning algorithm on the positioning accuracy, and actual offshore measurement was carried out to confirm the validity of the proposed positioning algorithm. Ocean is a very complex flexible system, and how to introduce a detailed algorithm about the sound velocity profile in order to improve its positioning accuracy is a problem that is to be discussed. This method is expected to be applied to more underwater activities as people pay more attention to ocean.

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