Study on the Calibration Method of USBL System Based on Ray Tracing

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***Abstract* — Positioning error analysis and install error calibration method are important technical issues for the Ultra Short Baseline (USBL) positioning system to be solved to improve the positioning precision. In this paper, the influences of each kind of error source are firstly analyzed in theory formula and simulation. It is found that installation error is the more prominent one, which is needed to be calibrated before its actual application. However, the calibration method based on the average sound speed will transfer the error introduced by acoustic ray bending into the installation error directly and it also will cause a great deal of loss for positioning precision. So an installation error calibration method of USBL system based on ray tracing is proposed here to improve this problem. Simulation and field experiment data processing prove that this new method can reduce the error caused by sound speed profile.**

Keywords — Ultra-short Base Line (USBL), installation error calibration, ray tracing

I. Introduction

With the more and more wide application of ultra-short baseline (USBL) system in the ocean exploitation, there is an increasing demand for higher and higher positioning precision. So the positioning error analysis and install error calibration method have become the important technical issues to be solved to improve the positioning precision.

As is known, USBL also need to get the absolute position of target of interest in geodetic coordinate, besides the relative position to array plane. Its basic idea is coordinate transformation with the acoustic positioning results and high-precision on-board gyrocompass, attitude sensor and DGPS combined, and determine the location or track of underwater target in geodetic coordinate finally. The main influence factors on the positioning precision of USBL system include the errors of system itself, measurement errors of ocean ambient parameters and installation errors caused by acoustic array. In this paper, we firstly analyze the influence of each kind of error source. Then it is found that installation error is the more prominent one, which is needed to be calibrated before its actual application. However, the calibration method based on the average sound speed will transfer the error introduced by acoustic ray bending into the installation error directly and it also will cause a great deal of loss for positioning precision. So an installation error calibration method of USBL system based on ray tracing is proposed here to improve this problem. Simulation and field experiment data processing prove that this new method can reduce the error caused by sound speed profile.

II. USBL Error Analysis

USBL principle can be expressed as following equation [1]-[4] :

$$ {}^{L}\vec{X}_{R} = {}^{L}\vec{X}_{G} + {}^{L}_{S}R \cdot {}^{S}_{A}R \cdot {}^{A}\vec{X}_{R} + {}^{L}_{S}R \cdot {}^{S}\overrightarrow{PX} \qquad (1)$$

where, ${}^{L}\vec{X}_{R}$ is target coordinates in the earth coordinate system with the unit of meter; ${}^{L}\vec{X}_{G}$ is geodetic coordinates of the GPS antenna center with the unit of meter; ${}^{L}_{S}R$ is rotation matrix from the ship coordinate system to geodetic coordinate system; ${}^{S}_{A}R$ is rotation matrix from array coordinate system to the ship coordinate system; ${}^{A}\vec{X}_{\mathrm{R}}$ is transponder coordinates in the array coordinate system with the unit of meter; ${}^{S}\Delta\vec{X}$ is array deviation error with the unit of meter.

We have analyzed USBL positioning error in theory before. In [3], main error sources of the system were listed including GPS, attitude, acoustic measurement error and array installation error. Then taking the positioning error of X axes as an example, by differentiating both sides of the equation. In addition, simulation was also implemented under 2 meters GPS error, 3 meters position bias between array and GPS antenna, 0.5% slant range acoustic positioning error, 0.5 degree attitude sensor error and installation angle conditions separately. Simulation results are listed in Table I and Table II.

TABLE I USBL POSITIONING ERROR

Positioning Error /(%R)	100m Distance	500m Distance	1000m Distance
GPS	2	0.4	0.2
Position Bias	3	0.6	0.3
Acoustic Measurement	0.5	0.5	0.5
Attitude Measurement	1.1	0.9	0.9
Installation Angle	0.9	0.9	0.9

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TABLE II USBL POSITIONING ERROR PERCENTAGE

Positioning Error Percentage	100m Distance	500m Distance	>1000m Distance
GPS	27%	12%	7%
Position Bias	40%	18%	11%
Acoustic Measurement	7%	16%	18%
Attitude Measurement	14%	27%	32%
Installation Angle	12%	27%	32%

As can be seen from Table I, GPS positioning error and position bias error introduce more positioning error at small slant range, and their influences become less and less with the increase of slant range. The positioning errors introduced by acoustic positioning error and installation deviation angle show no obvious change with the slant range. But the influence of attitude error is also related to position bias error, which results in the more error than that introduced by installation deviation error at small slant range. With the increase of slant range, when position bias error is equivalent to slant range in size, the influence of the same attitude error and installation deviation angle becomes constant. These ideas may have a good indication by Table II, i.e. at small slant range, GPS error and position bias error have a leading influence on the whole positioning system; at large slant range, acoustic positioning error, attitude error and installation deviation angle error become dominant factors.

III. III CALIBRATION ALGORITHM

The study above indicates that attitude error and installation deviation angle error affect USBL performance much. The accuracy of attitude sensors is better than 0.1 degree nowadays. So installation angle error is the main error source. To decrease its influence, installation error calibration procedure must be taken before usage. So the performance of the calibration algorithm is important.

Generally, we can calculate installation angles by using the conversion form of (1) when transponder position and the bias between array and GPS antenna are known, in which the solution is directly on the basis of each coordinate in every coordinate system.

$$ {}^{L}\vec{X}_R - {}^{L}\vec{X}_G - {}^{L}_{S}R \cdot {}^{S}\overrightarrow{PX} = {}^{L}_{S}R \cdot {}^{S}_{A}R \cdot {}^{A}\vec{X}_R \qquad (2) $$

However, when taking sound velocity profile into consideration, this model is not accurate enough. The left side of (2) is geometry relationship between the array and the transponder, while the right side is the acoustic relationship between the two, which can be influenced by sound velocity profile.

As Fig. 1 shows, acoustic ray will bend when sound velocity is not uniformly distributed. Then the USBL measured angle is the incidence angle of the ray and the measured coordinates are virtual positions. Therefore the installation angle calibrated by (2) contains error caused by sound velocity profile, which must be corrected to improve system accuracy. That's the reason we develop a new algorithm based on ray tracing theory.

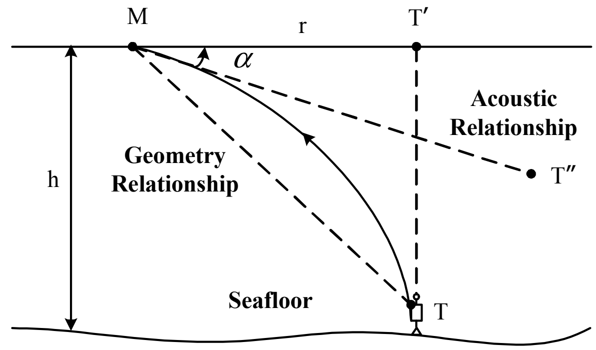


Fig. 1. Acoustic positioning with sound velocity profile affects

In the new algorithm we use acoustic relationship to form the equation.

$$ {}^{S}_{A}R \cdot \cos\vec{\Theta}^{T} = \cos\vec{\Phi}^{T} \cdot {}^{L}_{S}R^{T} \qquad (3) $$

Where $\vec{\Theta}$ is the incidence angle vector of the acoustic ray in array coordinate; $\vec{\Phi}$ is the incidence angle vector of the acoustic ray in geodetic coordinate. $\vec{\Theta}$ can be directly measured by USBL system, while $\vec{\Phi}$ can be calculated by ray tracing theory.

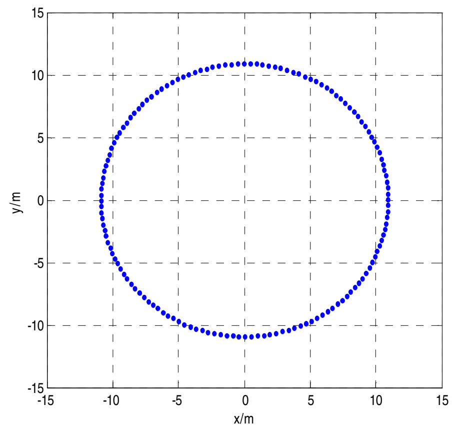
Suppose transponder geodetic position is known or can be measured by LBL method at tens of centimeter level in deep water [6]. Geodetic position of the USBL array can be calculated by GPS, attitude sensor and the bias between GPS antenna and array. Sound velocity can be measured by SVP (Sound Velocity Profile) or CTD. Using this information, Snell Law [7] in the acoustic ray theory can calculate $\vec{\Phi}$ by iteration.

After all the parameters in (3) are known, we can get the azimuth installation angle α , pitch installation angle β and roll installation angle γ via Gauss-Newton method.

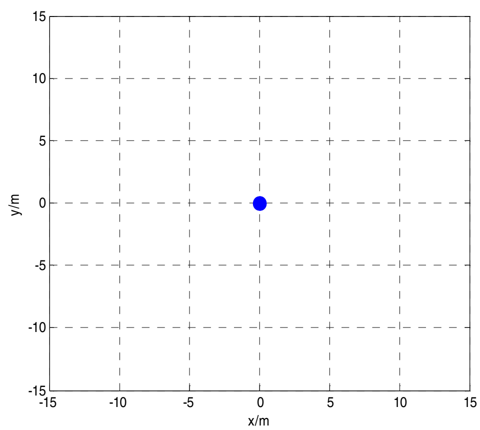
To compare the calibration performance of the general method and the ray tracing method, simulation was implemented under the condition of a 2000m depth MUNK sound velocity profile [8] and no other measurement error. The calibration residual of both methods are listed in Table 3. It is obvious from the simulation results that the ray tracing method can accurately calibrate the installation error while the general one has some residual caused by sound velocity profile. We fix the USBL system by calibration results of the two methods and then positioning scatters is got as Fig. 2 shows. During the position simulation, ship sails around the transponder with a 1000m radius round track. The scatters fixed by general method's results share the same shape of the track, which means systemic errors haven't been totally cancelled by calibration. The scatters fixed by ray tracing method's results are close to just one single point. Obviously, calibration residuals have been eliminated by the introduction of ray tracing theory.

TABLE 3. COMPARISON OF DIFFERENT CALIBRATION METHODS

Installation Error Residual	$\Delta\alpha(°)$	$\Delta\beta(°)$	$\Delta\gamma(°)$
General Method	0.036	0.302	0.135
Ray Tracing Method	0.00	0.00	0.00



(a) Fixed by General Method Calibration Results



(b) Fixed by Ray Tracing Method Calibration Results

Fig.2. Fixed Positioning Scatters

Therefore it can be concluded that if all the measurement data is accurate, the ray tracing method is free of sound velocity influence. In addition, more study must be done in the future when sound velocity measurement error exits or sound velocity varies with time.

IV. IV FIELD EXPERIMENT AND DISCUSSION

October 2012, at Songhua Lake, Jilin Province, China, this calibration method was tested by field experiment. Calibration data was collected by USBL system developed by Harbin Engineering University, with the assisting devices including Leica RTK-GPS, OCTANS gyro and AML SeaCast SVP. In the experiment, we firstly moored the transponder at 50m depth. Sound velocity profile was measured by SVP while waiting the transponder to be stable in its position.

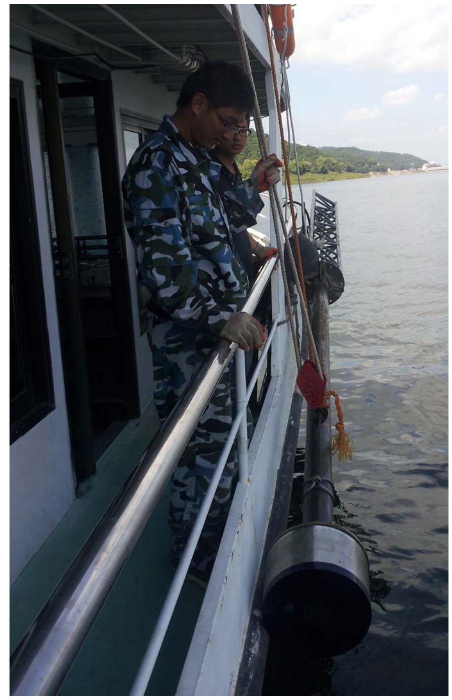


Fig. 3. USBL array and its intallation

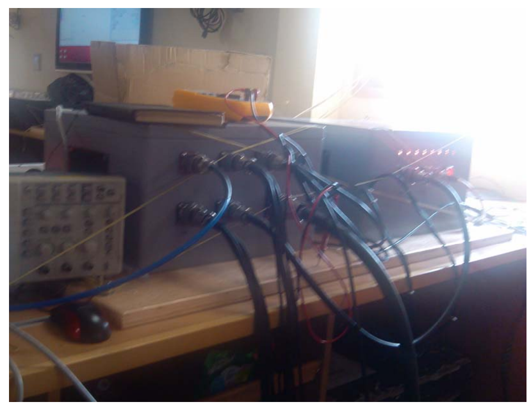


Fig. 4. USBL processor and power box

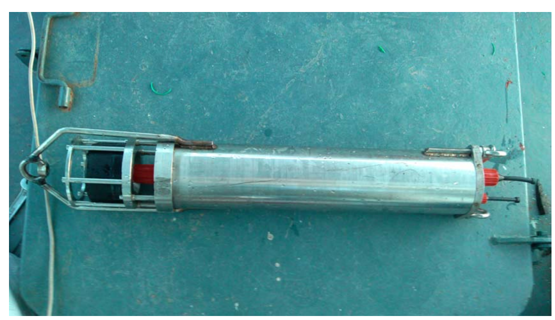


Fig. 5. Transponder

After the profile was measured, raw data was processed by the following procedure: Firstly, the downcast data was selected because of its accuracy. Then the selected data was smoothed by filter and sample to reduce the time which will be cost in the ray tracing calculation. Finally, we got the sound velocity profile shows in Fig. 6.

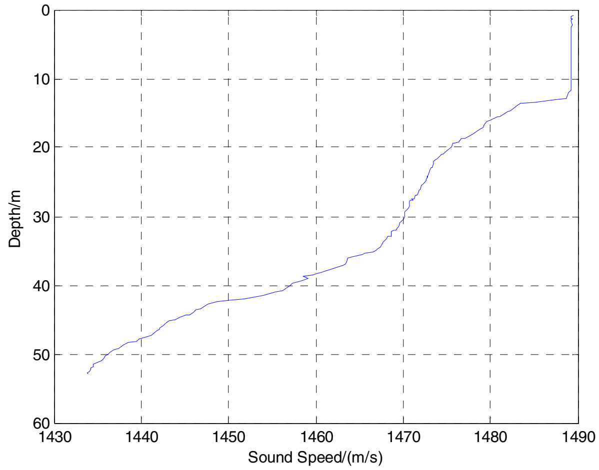


Fig. 6. Managed Sound velocity profile

Next, ship with the USBL system sails around the transponder and measure the time delay between them. Meanwhile, the ship position and gesture were collected by GPS and gyro respectively. The ship sailed in two different kinds of radius, 60m and 90m, in order to check the influence of sound velocity profile at different incidence angles.

Experiment data was processed by the two methods mentioned above. Calibration results are listed in Table 4, in which R60_1 to R60_3 correspond to 60m radius tracks, R90_1 to R90_3 correspond to 90m ones.

It can be seen in Table IV that the general method calibration results are different between 60m and 90m tracks especially in β and γ. Difference in β is about 0.2 degree and 0.1 degree in γ.

According to ray tracing theory, there is bias between geometry angle and incidence angle, as Fig. 1 shows. This bias will increase with the decrease of the incidence angle, which means sound velocity's influence on calibration accuracy varies with the incidence angle. The same installation angle will be calibrated into different results because of the incidence angle variety generated by track radius changes. That why different radius tracks correspond to different calibration results. Moreover the incidence angle is angle in the vertical plane. So its affect will contribute more to the one with vertical component, namely β the installation angle in roll and γ the installation angle in pitch.

Compared with the general method, the calibration results' differences of the ray tracing method are smaller. Difference in β is about 0.1 degree and 0.01 degree in γ. This improvement owes to the ray tracing theory. Though the new method doesn't eliminate the difference between tracks, we guess it is caused by the fact that USBL precision is relate to the angle between the transponder and the array, and maybe caused by profile measurement error. Generally, the effectiveness of the ray tracing calibration method is obvious.

TABLE IV CALIBRATION RESULTS OF DIFFERENT METHODS

Calibration Results /Deg	**By General Method**			**By Ray Tracing Method**		
	α	β	γ	α	β	γ
R60_1	1.05	-0.43	2.44	1.07	-0.46	2.72
R60_2	1.07	-0.43	2.45	1.09	-0.46	2.73
R60_3	1.09	-0.42	2.42	1.10	-0.44	2.71
R90_1	1.06	-0.23	2.31	1.08	-0.32	2.71
R90_2	1.10	-0.29	2.32	1.11	-0.33	2.71
R90_3	1.12	-0.30	2.31	1.13	-0.35	2.70

V. SUMMARY

This paper mainly introduces a new calibration model based on ray tracing theory. Firstly, the error sources of USBL system are listed based on its principle formula. By differentiating the principle formula, error transfer equation is obtained and the character of each error source is studied by the equation. Calculation results in the simulation show that the installation angle error contributes the most. So installation calibration is a necessary procedure in USBL usage. So the performance of the calibration algorithm is important. Generally, installation angles are calculated by using the conversion form of the principle formula. However, when taking sound velocity profile into consideration, this system error exists in the general model. Therefore we design a new calibration algorithm based on ray tracing theory. Simulation and field experiment data processing prove that this new method can reduce the error caused by sound speed profile. Although more work should be done to evaluate this method's performance under many kinds of measurement errors, its effectiveness to eliminate system error in the general model can't be denied.

REFERENCE

[1] J.Opderbecke. At-sea calibration of a USBL underwater vehicle positioning system. OCEANS '97. MTS/IEEE. 1997

[2] Min Yu. In-situ Calibration of Transceiver Alignment for a High-precision USBL System. ICCASM2010,2010

[3] Cuie Zheng, Jin Gui. Error Analysis for Ultra-Short Base Line Positioning System .ISAET2010, 2010.

[4] CuieZheng. Application of USBL Positioning Technology on Underwater Submersible Interfacing Calibration of Transducer and Transponder Positions. Harbin: Harbin Engineering University, 2008 (in Chinese)

[5] Yanxiong Liu, Lin Peng, Yongting Wu. Geomatics and Information Science of Wuhan University. [J]. Geomatics and Information Science of Wuhan University,2006, 31(7): 610-617(in Chinese)

[6] Masayuki Fujita, Tadashi Ishukawa .etc. GPA/Acoustic seafloor geodetic observation: method of data analysis and its application. Earth Planets Space, 58, 265-275, 2006.

[7] Cohen and Einsfein. Continuous Gradient Ray Tracing System, U. S. Nav. Underwater Syst. Center. Rep. 1069, 1970

[8] W. Munk. Sound Channel in an Exponentially Stratified Ocean, with Application to sofar JASA, 55, 220, 1974