Sound Speed Profile Estimation by Multi-static Configuration

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***Abstract*—A new sound speed profile estimation was proposed at the previous conferences. A new model was introduced using single sonar with multi layer structure. It is effective for frequent estimation which is required to grasp detection coverage in dynamical changing environments or highly secure areas. One of the problems is the estimation consumes much measurement time for higher accuracies, since multiple transmissions are necessary to solve the simultaneous equations. For reducing measurement time, a simple multi-static concept is presented in this presentation. If the sonars are located on the same depths or depth differences are small, this approach is effective. Another problem caused by computing time is severe for higher accuracies and it is hard to overcome. A new profile model has a possibility for accelerating calculations. The new model and its effects are still under investigation.**

Keywords—underwater acoustics; sound speed profile; harbor protection; multi-static

I. INTRODUCTION

In these decades harbor protection importance is increasing both in commercial and military usages. Lots of systems are proposed with cameras and radars for harbor protections. Although above water threads are one of the largest issues to tackle, underwater threads should be paid attention more widely, because it is very difficult to detect underwater targets. Some security systems apply acoustical sensors for underwater surveillances. Detection coverage by the sensors must be kept under control for effective operations. Sound propagation evaluations are required for sensor coverage estimations. Hence, sound profile estimations become essential for the coverage evaluations.

In usual sonar operations, expendable devices like XBTs and XCTDs are utilized for sound profile estimations. However, these are not practical for frequent measurements and they will become obstacles for ship navigations. Moreover, these devices measure temperature and salinity distributions, they does not measure sound speed directly. On the other hand, sound speeds are directly measured in acoustical tomography. But the buoys tethering sensors will become nuisances and they are hard to remove or move quickly.

A new approach for sound speed profile estimation was proposed using single sonar to solve this problem [1][2]. It is thought to open a new sonar operation style. However, it consumes much time for higher accuracy estimations, because multiple angle transmissions need multiple waiting time and averaging to suppress surface fluctuation influences also need lots of time. This requirement is not favorable for quick sonar operations. One of the ideas reducing estimation time is using multiple sonars. The multiple sonar arrangements are discussed in the next section. A multi-static configuration is also valid for reducing measurement time. After that a new sound speed model is shown for changing the situation of the calculation accelerations.

II. MULTI-STATIC CONFIGURATION

Originally, using single sonar is one of the largest attractive points of our new idea. The basic concept is schematically shown as Fig.1. The ocean is divided by layers and the sound speed is assumed to be constant in each layer. A sonar on the bottom transmits for the surface and receives scattered sounds. The sound speed in each layer is calculated using traveling periods of various transmission angles. The simultaneous equations obtained traveling time measurements are non linear. Some conventional optimization techniques including the Newton-Raphson and the bi-section are tried to solve this equations. All of them did not provide valid solutions, since the solution space is extremely complicated, and there are huge numbers of local minimums. Therefore, the simplest method which searches all parameter space is the best approach for this equations at present.

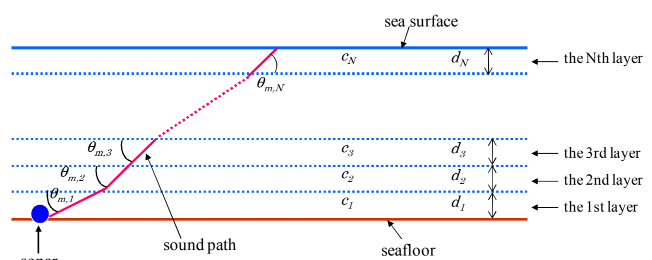

Fig. 1. Single sonar configuration.

Even if multiple sensors are required in the security systems for a wide area coverage, they are easily arranged since each sonar is independent for sound speed estimations. As a matter of course, interference must be avoided among sonars using time division, frequency division or code division

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like cellular phone networks. Under the assumption that the sound speed profile is constant in the area containing multiple sonars, measurement time is reduced by simultaneous transmissions with different angles among sonars. Unlike cellular phones, interferences are sometimes inevitable and hard to eliminate in underwater acoustics. The simplest solution is using multiple sonars in the multi-static configurations. This method utilizes single transmitting sonar and multiple receiving sonars. The transmitter is also a receiver as a usual multi-static sonar. All sonars are located on the bottom. A configuration example is shown in Fig.2. Since only the single transmitter is used, it is not needed to consider interferences caused by other transmitters. If multiple transmitters are required for wide or complex area coverage, the flexibility is larger than multiple mono-static sonar configurations, because distances among transmitters are able to be larger than mono-static sonars.

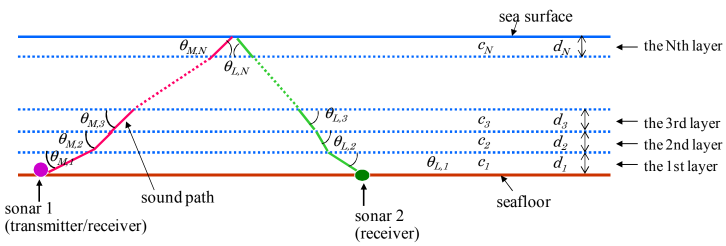

Fig. 2. Example of multi-static layered model configuration.

From this Fig.2 example, the sound traveling duration from the surface to the transmitting and receiving sonar 1 becomes

$$T_M = \sum_{i=1}^{N} \frac{d_i}{c_i \left\{ 1 - \left(\frac{c_i}{c_1} \right)^2 \cos^2 \theta_{M,1} \right\}^{1/2}} \tag{1}$$

as in the previous papers[1][2], and the duration from the surface to the receiving only sonar 2 is

$$T_L = \sum_{i=1}^{N} \frac{d_i}{c_i \left\{ 1 - \left(\frac{c_i}{c_1} \right)^2 \cos^2 \theta_{L,1} \right\}^{1/2}} \tag{2}$$

The latter time is calculated using the traveling time from the sonar 1 to sonar 2 and the former time which is half of the elapse time between the transmitting and receiving at sonar 1. Therefore, the 2 angle case equations are obtained at one transmission. This means profile estimation efficiency is doubled by two sonars if the transmitting angles at sonar 1 and receiving angles at sonar 2 are always different. Therefore, measurement time is reduced to $1/(N-1)$ by using N receiving sonars. Multiple sonar also helps to increase accuracy provided by averaging. There is a tradeoff between the accuracies and the cost which is affected by the sonar number.

Although this new concept uses multiple sonars like acoustical tomography systems, it is suitable for harbor protections, since all sonars on the bottom do not become obstacles for ship navigations unlike tethered arrays used in acoustical tomography. And it can be said that multiple sonars should be deployed for covering wide and complex harbor areas with networks. Under this situation, a multi-static operation is a natural conclusion for harbor security. Multi-static operations are also useful for protection operations, since there are numerous advantages like acquiring multiple aspects of targets, different reverberation environments among sonars, covertness of receiving sonars and so on.

Sound profile's horizontal distributions are derived when multiple sonars are used under the assumption that sound speed profiles are different among sonars, instead of reducing measurement time under the assumption of constant sound speed profile. It should be noticed that estimated distribution resolutions are worse than mono-static case for multi-static sonars, because the sound speed profile is constant in the area containing a transmitter and receivers, and the area is larger than single mono-static sonar area.

III. More Practical Configurations

Equations (1) and (2) tacitly assume that all sonars are located on the same depth. Practically, it is sometimes very difficult to set up all sonars on the same depth because of the various submarine topographies. If the depth difference is small, the problem is evaded by setting the base line to the shallowest sonar as in Fig.3. The sound speed in the layer 0 beneath the base line is measured by the direct path propagation. Then other speeds for each layer are calculated using the simultaneous equations like flat bottom case. The direct path requirement is sometimes difficult because of large rocks, hills, corals and seaweeds. Setting a sonar on a stand becomes solution of this problem. And more, bottom reverberations must be serious, since the sound travels along the bottom. If this base line approach is applied for large depth differences among sonars, derived sound speed accuracies must be worse than flat bottom conditions.

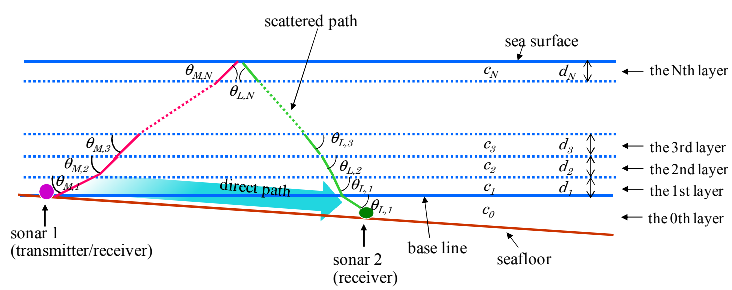

Fig. 3. A configuration sonars are located on an inclined bottom.

These speculations are based on an extrapolations of linear simultaneous equation cases. It is possible that different tendency is found in the non linear equations of our model. If the simultaneous equations are linear, they are solvable under a condition of full rank. A typical example equations for an explanation are described as

$$\begin{pmatrix} T_1 \\ T_2 \\ \vdots \\ T_N \end{pmatrix} = \begin{pmatrix} a_{11} & 0 & \cdots & 0 \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_N \end{pmatrix} \tag{3}$$

Although elements are zero in the 1st line except the 1st element, solutions exist under the full rank condition of the matrix. This means that if the equations are transformed to such linear equations with an special approximation, the same depth location is not always required.

An approximation is tried, but the result provided no solution. The approach is explained bellow because it is a good example of what not to do. The m-th term in the summation of (1) is modified to

$$\tau_{M,m} = \frac{d_m}{c_m \left\{ 1 - \left(\frac{c_m}{c_1} \right)^2 + \left(\frac{c_m}{c_1} \right)^2 \sin^2 \theta_{M,1} \right\}^{1/2}} \tag{4}$$

Supposing the approximation condition

$$\left| 1 - \left(\frac{c_m}{c_1} \right)^2 \right| < \left| \left(\frac{c_m}{c_1} \right)^2 \sin^2 \theta_{M,1} \right| \tag{5}$$

Equation (4) is approximated to

$$\tau_{M,m} \approx \frac{d_m}{c_m \left(\frac{c_m}{c_1} \right) \sin \theta_{M,1}} \left\{ 1 - \frac{1 - \left(\frac{c_m}{c_1} \right)^2}{2 \left(\frac{c_m}{c_1} \right)^2 \sin^2 \theta_{M,1}} \right\} \tag{6}$$

taking into account up to the 1st order of (5). This approximation produces the following simultaneous equations by $2N-1$ measurements.

$$\mathbf{\Theta} \cdot \mathbf{\Xi} = \mathbf{T} \tag{7}$$

where

$$\mathbf{\Theta} = \begin{pmatrix} \frac{d_1}{\sin \theta_{1,1}} & \frac{d_2}{\sin \theta_{1,1}} & \frac{d_2}{\sin^3 \theta_{1,1}} & \cdots & \frac{d_N}{\sin \theta_{1,1}} & \frac{d_N}{\sin^3 \theta_{1,1}} \\ \frac{d_1}{\sin \theta_{2,1}} & \frac{d_2}{\sin \theta_{2,1}} & \frac{d_2}{\sin^3 \theta_{2,1}} & \cdots & \frac{d_N}{\sin \theta_{2,1}} & \frac{d_N}{\sin^3 \theta_{2,1}} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{d_1}{\sin \theta_{2N-1,1}} & \frac{d_2}{\sin \theta_{2N-1,1}} & \frac{d_2}{\sin^3 \theta_{2N-1,1}} & \cdots & \frac{d_N}{\sin \theta_{2N-1,1}} & \frac{d_N}{\sin^3 \theta_{2N-1,1}} \end{pmatrix}$$

$$\mathbf{\Xi} = \left(\frac{1}{c_1}, \frac{1}{c_2 \left(\frac{c_2}{c_1} \right)}, -\frac{\left\{ 1 - \left(\frac{c_2}{c_1} \right)^2 \right\}}{2 c_2 \left(\frac{c_2}{c_1} \right)^3}, \ldots, \frac{1}{c_N \left(\frac{c_N}{c_1} \right)}, -\frac{\left\{ 1 - \left(\frac{c_N}{c_1} \right)^2 \right\}}{2 c_N \left(\frac{c_N}{c_1} \right)^3} \right)^{\mathrm{T}}$$

$$\mathbf{T} = \left(T_1, T_2, \cdots, T_{2N-1} \right)^{\mathrm{T}}$$

Although this approximation seems to work well, the determinant of the matrix $\mathbf{\Theta}$ is zero. Hence there is no solution.

IV. POLYGONAL LINE MODEL

A multi-static configuration reduces the total estimation time reducing measurement time. Another and the largest problem is computing time as mentioned in the previous presentation. Table I indicates how large the computational time is. These are result of the numerical simulations with the newest Core i7 PC. Fortunately, most of the simulation accuracies are acceptable for 2 m/sec of initial searching step size in the pyramid search. However, that is not assured theoretically. If the best initial step size is 1 m/sec and searching area is 100 m/sec as in the numerical experiments, searching space rapidly increases multiplied by 100 times for adding one layer in the model. Hence when 10 layers are required, more than 3×10^{10} hours must be consumed for estimation from this table. This astronomically large number is not realistic even if a super computer is carried out.

After all, an optimal approach is indispensible for this problem. Usual optimal methods are not applicable to these non linear equations because of the complicated solution space of the non linear equations as mentioned in the previous presentations. However, there are various optimization procedures for solving non linear equation other than methods validated in the simulations. Lots of methods are popular and effective in some regions dealing non linear problems. The methods include neural networks, genetic algorithms, simulated annealing. However, from my experiences, bad behaviors in the simulation of the bisection and the Newton Raphson often lead to the similar behavior in those powerful non linear optimizations. Model construction should be considered before trying various techniques.

TABLE I. REPRISENTATIVE COMPUTING TIMES FOR EACH STEP SEARCHING

Time (sec)	Maximum Searching Step Size (m/sec)	Search Area (m/sec)	Minimum Searching Step Size (m/sec)	Layer Number
0.18-0.27	10	1450-1550	0.5	5
4.26-4.31	5			
360-372	2			
10840-10930	1			

To overcome this entrapment situation, a new acoustical structure model may bring a new view point. Generally, if the sound speed is an arbitrary function of height z form the bottom, and the sound traveling time is described as

$$T_m = \sum_{i=1}^{N} \int_{h_{i-1}}^{h_{i-1}+d_i} \frac{dz}{c_i(z) \left\{ 1 - \left(\frac{c_i(z)}{c_1} \right)^2 \cos^2 \theta_{m,1} \right\}^{1/2}}$$

$$h_i = \begin{cases} 0 & (i = 0) \\ \sum_{k=1}^{i} d_k & (i > 0) \end{cases} \tag{8}$$

for the layered model in the case of which the sound speed is a function of depth. If the sound speed is constant for each layer, this model leads to the simple multi layer model which is proposed. It is natural to consider the sound function as a liner of depth for the next step.

If the function is assumed as

$$c_i(z) = c_{i-1} + g_i(z - z_{i-1}) \tag{9}$$

the traveling time becomes as

$$T_m = \sum_{i=1}^{N} \frac{1}{g_i} \left\{ \log\left(\frac{1 + \sqrt{1 - \frac{\cos^2\theta_{m,1}\{c_{i-1} + g_i(h_{i-1} - z_{i-1})\}^2}{c_1^{\ 2}}}}{c_{i-1} + g_i(h_{i-1} - z_{i-1})} \right) - \log\left(\frac{1 + \sqrt{1 - \frac{\cos^2\theta_{m,1}\{c_{i-1} + g(h_{i-1} + d_i - z_{i-1})\}^2}{c_1^{\ 2}}}}{c_{i-1} + g_i(h_{i-1} + d_i - z_{i-1})} \right) \right\} \tag{10}$$

Although polygonal line models like (9) are referred in some papers [3], this is the first time to integrate for estimating traveling time. This model is an extension of the bilinear profile model [4]. By these equations, the problem changes to searching optimum factor g_i from searching sound speeds in each layer. Although the problem has been changed, it is difficult to say that this new model is better than previous model. Equation (10) consists of logarithmic functions and it is more complex than the previous model. Usually, the complexity sometime brings more problems. The conclusion must be provided after numerical experiments

From the point of view of ray tracing, this model is equivalent to an assumption that the sound travels along a arc for each layer. This arc propagation is not unnatural and classic, and it is frequently discussed in the constant gradient model. One of the preferable features is that the sound speed continuities are kept between layers. A constraint has been considered in the original constant sound speed model to reduce computational time by restricting the parameter search space. This policy also brought discontinuity suppressions.

From (9) and (10), it is clear that one parameter is added since this model needs a basic sound speed adding to proportional parameters for each layer. However, the one parameter is easily decreased when one of the layer sound speed is assumed to be constant.

Other functions may break this situation. Anyway, it is clear that the integralibility is important from (8). If a complex function is chosen as a sound speed, and it is not able to be integrated, the problem becomes extremely difficult. The fact that a quadric function model cannot be integrated analytically indicates finding applicable functions is not a easy problem.

Some researches reconstruct sound speed profiles by empirical orthogonal functions derived by measurements [5]-[7] or mode decompositions [8][9]. These approaches are very attractive, but these functions are usually very complex and not easily integrated. And more, complicated environments are assumed for our applications. In the harbor, water is stirred by the sea, the river, and ship drains, the temperature structure is complicated, therefore, the sound speed profile becomes complicated. The basic policy of this research is the theory is applicable to any shape sound speed profiles. As in some measurements, sound speed profiles show diverse kinds of shapes and changes in short periods [10][11]. An extreme case which is occurred in special environment [12] should be also considered.

V. SUMMARY

For estimating sound speed profiles, a new approach was proposed in the previous conferences utilizing sound scattering at the surface with bottom based sonars. Although it is effective for frequent estimation for detection coverage in the security systems, it requires much measurement time and computational time. A multi-static configuration is proposed for reducing measurement time. It is effective if the depth differences are small among sonars. Large differences among sonar depths are practical, however, it is not clear whether multi-static configuration reduces measurements or not.

The largest problem is huge computational time. It may exceeds practical operation time largely for higher depth resolutions. Accelerations are still under investigation. Usual optimizations do not work well. As one of the trials of changing situations, new models of sound speed function have been evaluating. For model selections, integrability of a function is the most important. Though a polygonal line model is integrable, the results are more complicated than the original model in which the sound speed is constant at each layer. Anyway, numerical simulations are needed for deciding which model is effective.

The present accuracies of sound speed profiles are almost acceptable for our rough coverage estimations. But it is a big issue that the accuracies which are derived in the simulations are not assured theoretically. Our concern is based on the application environments where the sound speed profiles are complicated and change dynamically. Therefore, analytical investigations are important as well as numerical simulations. Moreover, a new sound speed profile model must be searched continuously before trying new optimizations.

REFERENCES

[1] H. Shiba, "Evaluation of Sound Speed Profile Estimation by Single Sonar," Proceedings of International Symposium on Underwater Technology 2013, March 2013.

[2] H. Shiba, "Layered Model Sound Speed Profile Estimation," *Proceedings of MTS/IEEE OCEANS 2013*, June 2013.

[3] H. Ramezani and G. Leus, "Ranging in an Underwater Medium with Multiple Isogradient Sound Speed Profile Layers," *Sensors 2012*, 12, pp. 2996-3017.

[4] H.-H. Chen, C.-C. Wang, W.-N. Chuang, B.-H. Lin, K.-H. Li, and J.-D. Su, "Linear and Bilinear Approximations of Sound Speed Profiles in GPS/Acoustic Seafloor Geodesy," *Proceedings of International Symposium on Underwater Technology 2013*, March 2013.

[5] J. C. Park and R. M. Kennedy, "Remote Sensing of Ocean Sound Speed Profiles by a Perceptron Neural Netwaok," *IEEE J. Ocean. Eng.,* vol. 21, no. 2, pp. 216-223, April 1996.

[6] O. Carriere, J.-P. Hermand, M. Meyer, and J. V. Candy, "Dynamic Estimation of the Sound-Speed Profile from Broadband Acoustic Measurements," *Proceedings of IEEE OCEANS 2007 Europe*, pp. 1-6, June 2007.

[7] Y. Yu and Z. Li, "Sound Speed Profiles Inversion in Shallow Water Using a Parallel Genetic Algorithm," *Proceedings of the Second International Shallow - Water Acoustics Conference* (*SWAC'09*), pp. 286-293, September 2009.

[8] E. R. St. Pierre and K. E. Wage, "Sound Speed Estimation from Sparse Environmental Measurements With Application To Mode Filtering, " *Proceedings of MTS/IEEE OCEANS 2005*, pp. 1345-1351, Sept. 2005.

[9] J. V. Candy and E. J. Sullivan, "Sound Velocity Profile Estimation: A System Theoretic Approach," *IEEE J. Ocean. Eng*., vol.18, no. 3, pp. 240-252, July 1993.

[10] C. Gostnell, "Efficacy of an interferometric sonar for hydrographic surveying: Do interferometers warrant an in depth examination?," The Hydrographic Jyournal, 118, pp.17-24, 2005.

[11] M. Weirathmueller, T. C. Weber, L. Mayer," Observations of High Frequency, Long Range Acoustic Propagation in a Harbor Environment," *Proceedings of WaterSide Security*, August 2008.

[12] J. R. Carpenter and M.-L. Timmermans, "Tempreture steps in salty seas," *Physics Today* vol. 65, No. 3, 2012.