Paper No.384/2022

UNDERWATER SOURCE LOCALIZATION USING CYLINDRICAL HYDROPHONE ARRAY AND RIEMANNIAN MATCHED FIELD PROCESSING

Tran Cao Quyen

Faculty of Electronics and Telecommunications, University of Engineering and Technology
144 XuanThuy, Cau Giay District, Hanoi Capital, Vietnam (+84) quyentc@vnu.edu.vn

Abstract: *The Matched Field Processing (MFP) is for defining the range and the depth of an underwater source effectively. However the algorithm is seldom used for finding the azimuthal direction of the source and is still not considered for multiple field replicas due to the variation of sound velocity. If using cylindrical hydrophone array (CHA) with 32x10 elements (ten ring with each ring of 32 elements) the rough azimuthal angle resolution,* $\Delta\theta_{3dB} \approx 9^0$*, is obtained. Then using TDOA (Time difference of arrival) of the two selected consecutive beams of CHA the system could provide the bearing accuracy up to* $\theta_{opt} \approx \Delta\theta_{3dB} / 80 \approx 0.1^0$*. Then, the range and the depth of the source are the solution of the proposed Riemannian MFP with the assumption of cylindrical spreading. The proposed RMFP is on the basis of Riemannian distance which is calculated directly by solving the geodesic equation on cylinder surface. The simulations show that only with the data from selected vertical hydrophone array of CHA (there are 32 vertical arrays on cylindrical array) is enough to locate the range and the depth of underwater source precisely.*

Keywords: *Cylindrical Array, Matched Field Processing, Riemannian Distance, Geodesics*

DOI: *1036336/akustika20224214*

1. INTRODUCTION

The Riemannian Matched Field Processing (MFP) usually uses horizontal or vertical hydrophone array in order to locate the range and the depth of an underwater source localization [1-7]. For the knowledge of the author, there are no paper deal with the combination of a cylindrical hydrophone array (CHA) and matched field processing. In this paper, we proposed using a CHA with MFP algorithm.

If using a CHA of 32x10 elements (10 rings with each ring of 32 elements) the rough azimuthal angle resolution, $\Delta\theta_{3dB} \approx 9^0$ is obtained. Then using TDOA (Time difference of arrival) of the two consecutive beams the system could provide the bearing accuracy up to $\theta_{opt} \approx \Delta\theta_{3dB} / 80 \approx 0.1^0$

The problem of there are many field replicas due to the variation of sound velocity is solved using a new Riemannian MFP. Then, the range and the depth of underwater source are defined using the suggested Riemannian MFP. Since we use a CHA so the cylindrical spreading of sound wave is the suitable assumption.

The proposed RMFP is on the basis of Riemannian distance which is calculated directly by solving the geodesic equation on cylinder surface.

We use parabolic approximation as the acoustic model and the measured data from a vertical hydrophone array from SACLANTC 1993 North Elba experiment. The simulations show that only with the data from selected vertical hydrophone array (there are 32 vertical arrays on cylindrical array) is enough to locate the range and the depth of underwater source precisely.

The paper is organized as follows. Part 2 introduces cylindrical hydrophone array and the procedure of using CHA with RMFP to find the azimuthal direction, the range and the depth of underwater source. Determination of azimuthal angle is described in Part 3. Part 4 is the measurement of directed Riemannian distance and Part 5 is Riemannian matched field processing. Some simulations are given in Part 6. Finally, we conclude the paper in Part 7.

2.CYLINDRICAL HYDROPHONE ARRAY

The geometry of a cylindrical hydrophone array of MxN elements is shown in Cartesian coordinate in Fig. 1 as follows

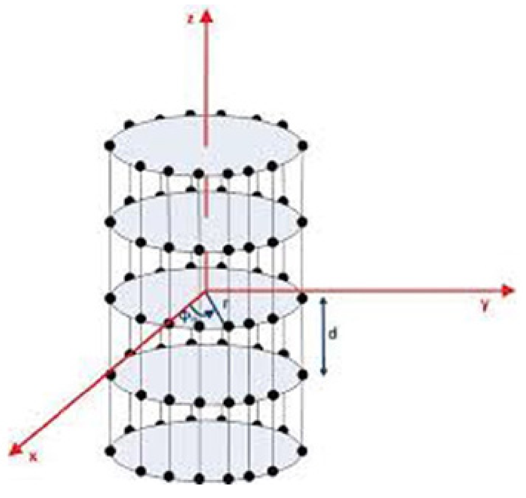

Fig. 1: The geometry of cylindrical hydrophone array of MxN elements (each ring has M elements)

In this case, the array factor is given by [8]

$$AF_{cylinder}(\varphi,\theta) = AF_{ring}(\varphi,\theta)AF_{linear}(\varphi,\theta) \quad (1)$$

where
$AF_{ring}(\varphi,\theta)$ is the array factor of the circular array [9]
$AF_{linear}(\varphi,\theta)$ in XOY plane andis the array factor of ULA-analog-PA in Z-axis.

Generally, the array factor of an array having ***M*** elements in space is given by

$$AF(\varphi,\theta) = I_1 e^{-j\beta\Delta r_1} + \cdots + I_M e^{-j\beta\Delta r_M} = \sum_{k=1}^{M} I_k e^{-j\beta\Delta r_k} \quad (2)$$

where
$\Delta r_k = r_k.a_r = x_k \cos\theta \sin\varphi + y_k \sin\theta \sin\varphi + z_k \cos\varphi$ is the phase difference of the ***Kth*** element to the reference element,
I_k is exited current of the ***K***th element,
r_k is position vector of the ***K***th element and
a_r is directional unit vector.

The directivity of an antenna can be approximated as [8]

$$D_{\max} = \frac{4\pi}{HPBW_\theta.HPBW_\varphi} \approx \frac{41253}{HPBW_\theta.HPBW_\varphi} \quad (3)$$

where
half power beam width in θ plane,
$HPBV_\theta$ is perpendicular to the half power beam width in φ plane, $HPBV_\theta$.

The procedure of using cylindrical hydrophone array with Riemannian MFP to find the azimuthal direction, the range and the depth of underwater source (***θ,r,z***) as Fig. 2 as follows

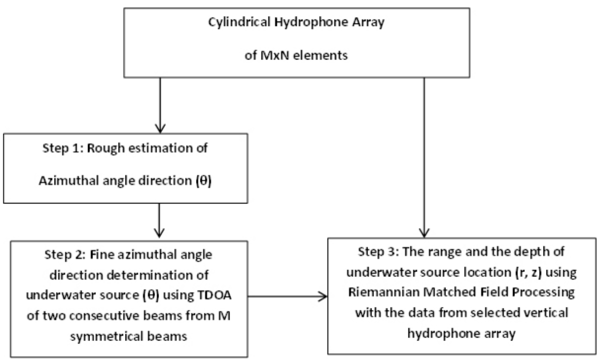

Fig. 2: The procedure of finding the azimuthal angle direction, the range and the depth of underwater source (θ,r,z)

The vertical hydrophone array in Step 3 is selected with azimuthal angle information from Step 2.

3. DETERMINATION OF AZIMUTHAL ANGLE DIRECTION

Using a ***CHA*** of ***MxN*** elements (***N*** rings with each ring of ***M*** elements), the array can produce ***M*** independent beams symmetrical in azimuthal plane. So rough azimuthal angle resolution,, $\Delta\theta_{3dB} \approx 360^0 / M$ is obtained. The desired azimuthal angle, ***θ***, corresponds to the beam of ***CHA*** with maximum received power.

The TDOA of the two consecutive beams of ***CHA*** in ***θ*** direction (left beam and right beam) denoted by ***τ(θ)***. The minimum variance of estimated TDOA is called $\Delta\tau_{min}$.

As in [11] whatever method is used the estimation accuracy is limited by the Cramer-Rao lower bound. In order to calculate the bearing accuracy, it is necessary to transfer the time delay ***τ*** to the incidental angle ***θ***. Of course, it depends on the array shape.

For a linear array with length ***L*** and $f_{rms} = \sqrt{f_1 f_2}, W = f_2 - f_1$ are root mean square of the frequency and bandwidth of the signal respectively. If ***T*** is the observation duration and SNR is the signal to noise ratio, the minimum variance of estimated TDOA is given by

$$\Delta\tau_{\min} = \frac{1}{2\pi} \times \frac{1}{\sqrt{2TW}} \times (f_{rms})^{-1} \times (SNR)^{-1} \quad (5)$$

If TW=500, SNR=1, the bearing accuracy is written by

$$\theta_{opt} = \frac{2\Delta\tau_{\min} c}{L} = \frac{c}{L\pi} \times \frac{1}{\sqrt{2TW}} \times (f_{rms})^{-1} \times (SNR)^{-1} \quad (6)$$

Therefore,

$$\theta_{opt} \approx \Delta\theta_{3dB} / 80 \quad (7)$$

4.DIRECTED RIEMANNIAN DISTANCE

4.1 GEODESIC EQUATIONS

According to [12], geodesic equations are equivalent to the system of differential equations as follows

$$\begin{cases} \Gamma^1_{11}(u')^2 + 2\Gamma^1_{12}u'v' + \Gamma^1_{22}(u')^2 + u'' = 0 \\ \Gamma^2_{11}(u')^2 + 2\Gamma^2_{12}u'v' + \Gamma^2_{22}(u')^2 + u'' = 0 \end{cases} \quad (8)$$

where
Γ^k_{ij} are Christofell symbols and
u, v are local coordinates.

4.2 SYMMETRIC AND KILLING VECTOR

Solving a system of second-order ordinary differential equations can be easy for simple metrics, but quickly become very difficult for more interesting cases. Here we exploit the symmetric of a manifold to simplify our tasks.

The simplest symmetries can be found by observing if the metric is independent of any of its coordinates. We can define a vector field for each symmetry such that, at every point, a vector points along the direction in which the metric does not change due to that symmetric. This is called a “Killing vector”, after the German mathematician Wilherm Killing.

For example, if we have a metric independent of x^1, the killing vector of the manifold in R^3 associated with that symmetry is

$$\xi^{\alpha} = (1,0,0) \tag{9}$$

The Riemannian distance between two point (m_a, m_b) is given by

$$L = \sqrt{p_{ij} x^i x^j} \tag{10}$$

where
p_{ij} is the Riemannian metric of the surface.

So, the Euler-Lagrange equation become

$$\frac{d}{d\sigma}\left(\frac{\partial L}{\partial(dx^1/d\sigma)}\right) = 0 \tag{11}$$

This means that the quantity inside the derivative is constant along the geodesic.

Now,

$$\begin{aligned} &\frac{\partial L}{\partial(dx^1/d\sigma)} = -p_{1\beta}\frac{1}{L}\frac{dx^{\rho}}{d\sigma} \\ &= -p_{\alpha\beta}\xi^{\alpha}u^{\beta} = -\boldsymbol{\xi}.\mathbf{u} = C^{te} \end{aligned} \tag{12}$$

where
ξ^{α} is a killing vector and
u^{β} is a velocity. Thus
$\boldsymbol{\xi}.\mathbf{u}$ is a conserved quantity. We can exploit this to solve geodesic equations.

4.3 GEODESIC EQUATION OF CYLINDRICAL SPREADING OF UNDERWATER SOUND WAVE

As is known, there are two kinds of underwater sound propagation, namely, Spherical and Cylindrical spreading. In this paper, the former is used.

Therefore, let us introduce the methodology of computing the geodesic equation by calculating the geodesic on the surface of the 3D cylinder.

The height of a 3D cylinder is a constant ***z=t***, therefore the Cylindrical coordinates are $(x^1, x^2) = (r, \phi)$, the Christofell symbols are

$$\Gamma^1_{ij} = \begin{bmatrix} 0 & 0 \\ 0 & -r \end{bmatrix}, \Gamma^2_{ij} = \begin{bmatrix} 0 & 1/r \\ 1/r & 0 \end{bmatrix} \tag{13}$$

The geodesic equations are obtained from (8)

$$\begin{cases} r'' - r(\phi')^2 = 0 \\ \phi'' + \dfrac{2}{r} r'\phi' = 0 \end{cases} \tag{14}$$

This couple of second-order ordinary differential equation is called geodesic equations.

The Riemannian distance between two points on the surface of 3D cylinder can be written as

$$L = \sqrt{(dr)^2 + r^2(d\phi)^2} \tag{15}$$

As is known, the first derivative of (12) give us the velocity, ***u***, as follows

$$\mathbf{u} = \frac{\partial L}{\partial s} = \left(\frac{dr}{ds}, r^2\frac{d\phi}{ds}\right) \tag{16}$$

If we divide both side of (15) by ds we obtain

$$1 = \left(\frac{dr}{ds}\right)^2 + r^2\left(\frac{d\phi}{ds}\right)^2 = \mathbf{u}.\mathbf{u} \tag{17}$$

Since the metric is independent of ***Ø***, we can choose the Killing vector as $\xi = (0,1)$

Therefore, the conserved quantity is

$$\boldsymbol{\xi}.\mathbf{u} = r^2\frac{d\phi}{ds} = b = C^{te} \tag{18}$$

From (17),(18), we deduce

$$\begin{aligned} \phi' &= \frac{b}{r^2} \\ r' &= \sqrt{\left(1 - \frac{b^2}{r^2}\right)} \end{aligned} \tag{19}$$

If we set r=1, $\phi' = C^{te}$ or $\phi = t$.

Now, the parameterization of the geodesic on the surface of 3D cylinder can be written as

$$(x^1, x^2, x^3) = (r = 1, \phi = t, z = t) \tag{20}$$

It is exactly the equation of Helix. Generally, the Helix equation in Cartesian coordinates are

$$\begin{cases} x = D\cos(\mathrm{t}) \\ \mathrm{y} = D\sin(\mathrm{t}) \\ \mathrm{z} = \mathrm{ht} \end{cases} \tag{21}$$

where
D is outer radius of the helix,
2πh is the pitch length of the helix.

5. RIEMANNIAN MATCHED FIELD PROCESSING

An acoustic pressure field on a vertical array of N sensors with locations $\boldsymbol{p}_a = (\boldsymbol{r}_a, \boldsymbol{z}_a), \boldsymbol{a} = \overline{\boldsymbol{1}, \boldsymbol{N}}$ and from the true source coordinate $\boldsymbol{p}_s = (\boldsymbol{r}_s, \boldsymbol{z}_s)$ is given by

$$\boldsymbol{F}_{\boldsymbol{p}_s}(\boldsymbol{p}_s, \boldsymbol{p}_a) = \boldsymbol{S}.\boldsymbol{G}(\boldsymbol{p}_s, \boldsymbol{p}_a) + \boldsymbol{W}(\boldsymbol{p}_a) \tag{22}$$

where
S is a spectral component of the source,
G is Green function which is calculated by Normal mode model and ***W*** represents uncorrelated additive ambient noise.

The cross-spectral density matrix is written as

$$\overline{\boldsymbol{R}}_{\boldsymbol{p}_s} = \sum_{m=1}^{M}\left[\boldsymbol{F}_{\boldsymbol{p}_s}\right]_m \left[\boldsymbol{F}_{\boldsymbol{p}_s}\right]_m^H \tag{23}$$

Normalization of CSDM using Frobenius norm, we have

$$\boldsymbol{R}_{\boldsymbol{p}_s} = \frac{\overline{\boldsymbol{R}}_{\boldsymbol{p}_s}}{\sqrt{\sum_{m=1}^{M}\sum_{n=1}^{M}\left|(\overline{\boldsymbol{R}}_{\boldsymbol{p}_s})_{mn}\right|^2}} \tag{24}$$

The Frobenius norm define that $\|\boldsymbol{A}\|_F^2 = \sum_{ij}\boldsymbol{a}_{ij} = tr(\boldsymbol{A}\boldsymbol{A}^H)$
where
a_{ij} is element of matrix A and
H is the transpose conjugate [13]. The corresponding normalization of CSDM of modeled field replica from estimated source coordinate $\boldsymbol{p} = (\hat{r}, \hat{z})$ denoted by $\mathbf{R}_{\mathbf{p}}$.

The matched field processor based on Riemannian Geometry is received by obtaining the space coordinates of modeled field replicas which are scanning over all modeled field replicas position $\hat{\boldsymbol{p}} = (\hat{r}, \hat{z})$ with a subject constraint of minimization of specific Riemannian distance.

According to (21) a new stochastic matched field processors which are based on directed Riemannian distance is defined as follows

First step:

Without loss the generality, the Riemannian matched field processor based on Riemannian geometry is received by obtaining the space coordinates of data replicas which are scanning over all modeled field replicas position with $\hat{\boldsymbol{p}} = (\hat{r}, \hat{z})$ a subject constraint of minimization of Riemannian distance as follows

$$(\hat{r}, \hat{z}) = \arg\min_{\mathbf{p}} \sqrt{tr(\mathbf{R}_{\mathbf{p}_s}) + tr(\mathbf{R}_{\mathbf{p}}) - 2\,\mathrm{tr}(\mathbf{R}_{\mathbf{p}_s}\mathbf{R}_{\mathbf{p}})} \tag{25}$$

Second step:

Now, on the basis of the outcome of directed Riemannian distance (Part II), we found that the geodesic distance of Cylindrical spreading is preferred to Helix distance. This mean that

$$\begin{aligned}
d_{\min} &= \min(d_1, d_{Helix})\\
d_1 &= \sqrt{tr(\mathbf{R}_{\mathbf{p}_s}) + tr(\mathbf{R}_{\hat{\mathbf{p}}_s}) - 2tr(\mathbf{R}_{\mathbf{p}_s}\mathbf{R}_{\hat{\mathbf{p}}_s})}\\
d_{Helix} &= \sqrt{(D\cos(t) - D\cos(\hat{t}))^2 + (ht - h\hat{t})^2}\\
(\hat{r}_s, \hat{z}_s) &= \arg\min_{\hat{\mathbf{p}}}(d_1, d_{Helix})
\end{aligned} \tag{26}$$

where

$$\begin{aligned}
&D = outer\ radius\ of\ Helix\\
&h = pitch\ length\\
&t = parameterization\ of\ modeled\ data\\
&\hat{t} = parameterization\ of\ measurement\ data
\end{aligned}$$

6. SIMULATIONS

6.1 ACOUSTIC MODEL

The acoustic model in this paper using Parabolic approximation model, in this case the acoustic pressure from [14] is given by

$$\Phi(r,z) = e^{i\frac{k_0}{2}(n^2-1)\Delta r}\,\Im^{-1}\left\{ e^{\frac{-i\Delta r k_z^2}{2ik_0}}\,\Im\{\Phi(r_0, z)\}\right\} \tag{27}$$

where
r is range,
z is depth,
$\boldsymbol{r_0}$ is the range of the source,
$\boldsymbol{\Delta r = r - r_0}$ is step size,
$\boldsymbol{k_0}$ is wavenumber of the source,
n is the refraction index of the medium and
$\Im$ is the Fourier transform.

6.2 INPUT ACOUSTIC DATA

Passive array data SONAR from SACLANTC1993 North Elba experiment available in Internet was used for processing [15]. The vertical underwater acoustic array data was collected in shallow-water off the Italia west coast by the NATO SACLANT Center in La Spezia, Italy. The original SACLANT time series has been converted to a series of MATLAB .mat files each of which contains a matrix “dat” that is 48 sensors by 64K data points long. Each file represents about 1 minute of data. The vertical array consists of 48 hydrophones with spacing 2 m between elements at total aperture length 94 m (18.7 m to 112.7 m in depth). The source emitted PRN signal with center frequency of 170 Hz.

The Sound Speed Profile (SSP) from [15] is described in Fig. 3.

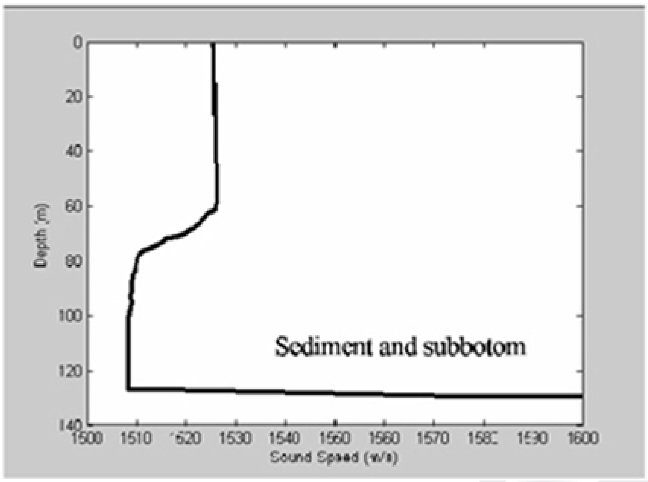

Fig. 3: SSP of SACLANTC 1993 North Elba

6.3 SIMULATION RESULTS OF GREAT CIRCLE ON THE SURFACE OF A SPHERE

We simulate the helix on the surface of the 3D cylinder with radius ***D=1, h=8***. The simulated result is shown in Fig. 4 as follows, in which, the helix is the red line.)

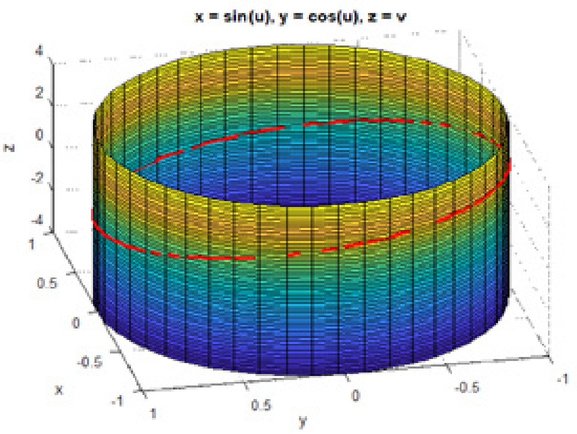

Fig. 4 The helix (red line) on the surface of the 3D cylinder.

6.4 SIMULATION RESULTS OF CYLINDRICAL HYDROPHONE ARRAY OF 32X10 ELEMENTS

When combining 10 rings in Z-axis with each ring spaced by λ/2 (half of wave length) we obtain the cylindrical hydrophone array of 32x10 elements. The array factor of the array is simulated (Eq.(1) and Eq.(2)) and depicted in Cartesian coordinate as in Fig. 5 as follows.

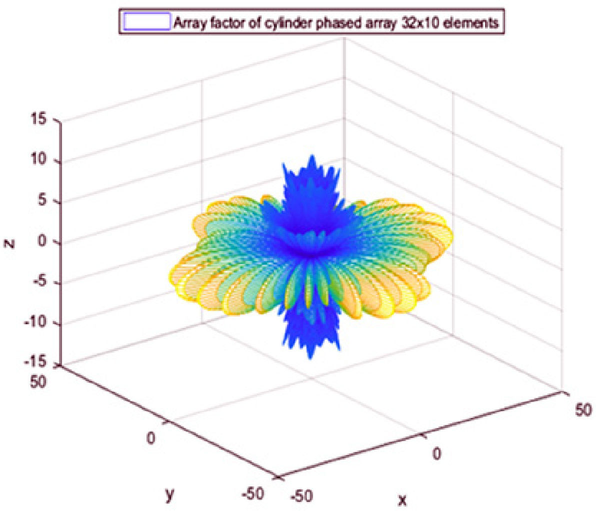

Fig. 5. The array factor of cylindrical hydrophone array of 32x10 elements. The result is reproduced from [10]

From the result in Fig. 2, we can see that the array can produce 32 independent beams symmetrical in azimuthal plane.

Since $HPBW_\theta = HPBW\varphi \approx 9^o$, the directivity of the Cylindrical hydrophone array of 32x10 elements can be approximated as

$$D_{cylinder} = \frac{41253}{(9).(9)} \approx 509 \approx 27dB \quad (4)$$

6.5 SIMULATION RESULTS OF BEARING ACCURACY

The bearing accuracy of circular array is the same form of linear array [11]. So if we use a CHA of 32x10 elements, the bearing accuracy up to $\theta_{opt} \approx \Delta\theta_{3dB} / 80 = 9/80 = 0.1^0$

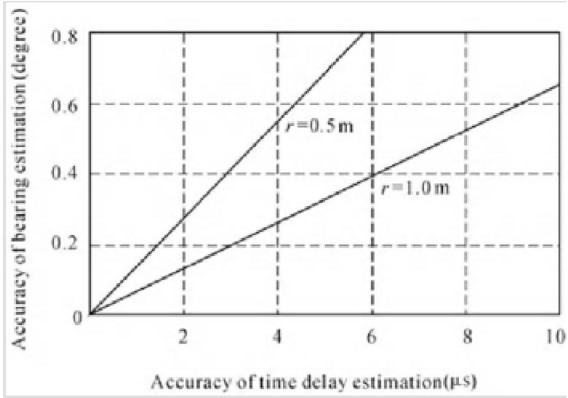

Fig. 6 Bearing accuracy of circle array (N=64 elements). The result is reproduced from [11].

6.6 SIMULATION RESULTS OF RIEMANNIAN MATCHED FIELD PROCESSING

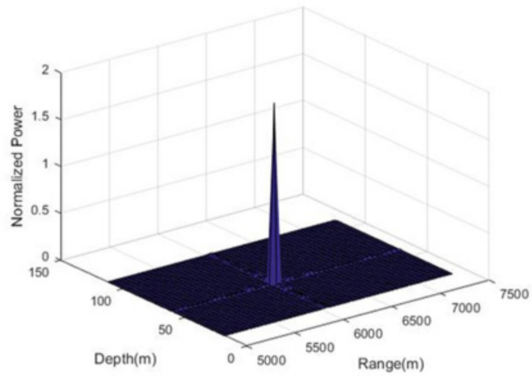

Fig. 7: Riemannian ambiguity surface for 20 modeled field replicas and 10 data replicas, SNR=-3dB, No of snapshot>20 sample in 3 dimensions

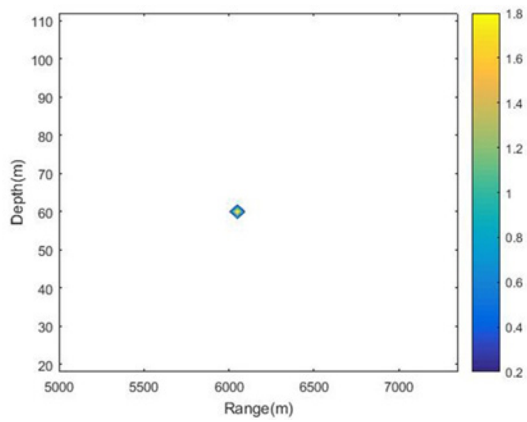

Fig. 8: Riemannian ambiguity surface for 20 modeled field replicas and 10 data replicas, SNR=-3dB, No of snapshot>20 sample in 2 dimensions.

Fig. 7 and Fig. 8 are obtained from RMFP in which only twenty modeled field and ten replica of SONAR array data were used. It should be noted that the data is from SACLANTC and SNR level is -3 dB and the number of snapshot is greater than 20 samples It can be seen that the true source can be detected at depth of 60 m and range of 6000 m.

The important thing is that the proposed RMFP could work in an uncertain ocean environment where there are a lot of modeled field replicas as well as replicas of SONAR array data whereas the conventional could not. It means that, the conventional MFP is very sensitive to an uncertain ocean environment, if there is a small changing of the replicas, one could not detect the true underwater source precisely.

The complexity of the proposed stochastic MFP is a little bit more than that other Riemannian MFP since it required the second step in part 3. However, almost SONAR systems now a day are supported by powerful microprocessors, so the speed of computation of the second step is only in few seconds.

A complete procedure of using CHA with RMFP to find the azimuthal direction, the range and the depth of underwater source is pointed out. The bearing accuracy, the range and the depth of underwater source are analyzed.

7. CONCLUSION

In this paper, we propose to use a cylinder hydrophone array of 32x10 elements with Riemannian matched field processing in order to locate an underwater source in 3D picture. A complete procedure of using CHA with RMFP to find the azimuthal direction, the range and the depth of underwater source is pointed out. The bearing accuracy, the range and the depth of underwater source are analyzed

The TDOA is used for determination of azimuthal direction with bearing accuracy of 0.1 degree. With the assumption of cylindrical spreading of underwater sound propagation, we found that the geodesic path in the fashion of Helix. The performance of the proposed RMFP is verified in simulations, the true source could be detected if 20 modeled field replicas and 10 replicas of SONAR array data were used. The performance of the proposed RTMP outperformed to that of standard algorithm at the expense of a little more of computation. In future, we will analyze the cooperation of towed array, flank array and CHA with RMFP.

The main applications of the proposed procedure are floating ship localization, submarine localization in military section and fish finding in civilization. A passive SONAR system which is embedded the proposed algorithms is suggested for the ships of Czech Republic Navy or cargo ships in commercial use.

ACKNOWLEDGEMENT

We would like to thanks SACLANTC for providing access of SONAR array data.

REFERENCES

[1] Tolstoy, A.: Matched Field Processing for Underwater Acoustics, World Scientific, 1993
[2] Tolstoy, A.: Application of matched field processing to inverse problems in underwater acoustics. IOP science, 16(6),p.1655-1666, 2000, DOI: https:// doi.org/10.1088/0266-5611/16/6/304
[3] Baggeroer, A. B., Kuperman. W. A., Mikhalevskey. P. N.: An overview of matched field methods in ocean acoustics. IEEE J. Ocean Engineering, 18 (4), p. 401-424, 1993
[4] Baggerorer, A. B.,Kuperman, W. A., Schmidt, H.: Matched field processing: Source localization in correlated noise as an optimum parameter estimation problem. J. Acoustic. Soc. Am. 83(2), p. 571-587, 1988
[5] Finettea, S., Mignerey, P. C.: Stochastic matched-field localization of an acoustic source based on principles of Riemannian geometry. J. Acoustic. Soc. Am 143 (6), p.3628-3638 ,2018
[6] Quyen, T. C.: Matched field processing for source localization based on an approach of Riemannian geometry, AKSUTIKA, Vol.33, pp.71-71, 2019.
[7] Quyen, T. C.: Stochastic matched field processing using directed Riemannian distance, AKUSTIKA, Vol. 40, pp.2-6, 2021
[8] Kraus, J.: Antennas, Second Edition, Tata McGraw-Hill, New Delhi, ISBN: 0-07-463219-1
[9] Jackson, B. R., Rajan, S., Liao, B. J and Wang, S.:DOA estimation using directive antennas in uniform circular array. IEEE Trans. Antennas. Propagation. Vol. 63(2). 2015. DOI: 10.1109/TAP.2014.2384044
[10] Quyen, T. C.: Phased Antenna Arrays toward 5G, Advanced Radio Frequency Antennas for Modern Communication and Medical Systems, Albert Sabban, IntechOpen, DOI: 10.5772/intechopen.93058.
[11] Li, Q.: Digital Sonar Design in Underwater Acoustics: Principles and Applications, Springer, London, New York, ISBN: 978-7-308-07988-4, 2012.
[12] Abdel-All, N. H., Abdel-Galil, E. I.: Numerical treatment of geodesic differential equations on a surface in R3. Int. Math. Forum, 8(1), p. 15-29, 2013
[13] Golub, G. H., Van Loan, C. F.: Matrix computations, The Johns Hopkins University Press ,1996
[14]Jensen, J. B., Kuperman, W. A., Porter, M. B., Schmidt, H.: Computational Ocaen Acoustics, Sringer Science, 2011
[15] http://spib.rice.edu/spib/saclant.html

Tran Cao Quyen *was born in 1976 in Hanoi, Vietnam. He was graduated Bachelor of Electronics and Telecommunications at Department of Electronics and Telecommunications, Hanoi University of Technology in 1999 and obtained his Master degree of Telecommunications at AIT (Asian Institute of Technology), in Bangkok, Thailand in 2001 and Ph.D in Electronics and Telecommunications from Vietnam National University, Hanoi in 2012. He is with the Faculty of Electronics and Telecommunications, University of Engineering and Technology (VNUH) from 2002 up to now where he has been a Faculty member. Beside giving several courses his major subjects are but not limited to Underwater Communication and Electromagnetic Engineering, Antenna and Propagations. He is also involved in some projects in SONAR for VNUH as well as for Vietnam Navy Academy.*