Investigation on beamforming solution for multi-receiver synthetic aperture sonar using CW pulse with sound velocity profiles in Vietnam's sea

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ABSTRACT

This paper proposes a novel beamforming solution for multi-receiver synthetic aperture sonar (SAS), which uses gated continuous-wave (CW) pulses, based on the average value of equivalent sound velocity (ESV) when considering the change of the sound velocity with depth. The main beam can be steered to desirable positions with the proposed solution. Besides, the computation time for the phase distribution from the proposed solution reduces compared with the conventional solution by dividing the propagation trajectory into straight lines, where the sound velocity is unchanged. The effectiveness of the proposed solution is validated and evaluated by the results of the beam pattern and the time for determining the phase distribution with the sound velocity profiles (SVPs) in Vietnam's sea.

Keywords: Synthetic aperture sonar; Beamforming; Equivalent sound velocity.

1. INTRODUCTION

SAS coherently processes the received signals at successive pings when the platform moves on a straight line to increase the aperture size [1]. With this principle, SAS can provide a high along-track (azimuth) resolution, which is not dependent on both range and frequency. To improve the area coverage rate, multi-receiver SAS is widely used in applications of small object detection, imaging of wrecks, and ocean survey [1, 2].

Beamforming for SAS is a particular case of the correlation algorithm when it is only interested in SAS images in the azimuth dimension [3]. When the wide pulses are transmitted, beamforming for SAS using CW pulses based on the delay and sum method can transform the determination of phase distribution for received signals. With the change of sound velocity according to depth, the calculation of delay time is quite complicated due to the separation of propagation trajectory into straight lines, where the sound velocity is constant [4]. To decrease the calculations, the average sound velocity from SAS depth to seafloor depth is used instead of SVP in the SAS processing [5]. However, the SAS imaging quality can be degraded due to the large difference between the average sound velocity calculated by the arithmetic mean of measured values and the real sound velocity, which expresses the delay time for determining phase distribution [5, 6].

Based on the use of ESV and the investigation of the change of ESV with the vertical inclination [7], this paper proposes a beamforming solution for multi-receiver SAS, which reduces the number of calculations of delay time (or ESV) compared with the conventional solution. The validation of the proposed solution is evaluated by analyzing the beam pattern, and the improvement of computation load is demonstrated by comparing the calculation time of phase distribution derived from two solutions based on MATLAB software with SVPs in Vietnam's sea.

The paper is organized as follows. Section 2 introduces the signal model of multi-receiver SAS. Section 3 presents a beamforming solution for multi-receiver SAS. Section 4 illustrates simulations, the results, and discussions. Finally, the last section concludes the paper.

2. SIGNAL MODEL OF MULTI-RECEIVER SAS

Because of the change of sound velocity according to depth, the sound is propagated in seawater according to the meandering path or the curve path. The signal propagation time between the two points is determined by dividing the propagation trajectory into straight lines with the constant sound velocity and then summing the propagation time in those lines. From the total propagation time, the process of sound wave propagation between two points A and B along a meandering path can be replaced by the propagation along a straight line with an equivalent sound velocity (ESV) as [7]:

$$c_{eq} = \frac{AB}{\tau_{\Sigma}} \tag{1}$$

where τ_{Σ} is the sum of wave propagation time in straight lines with the constant velocities.

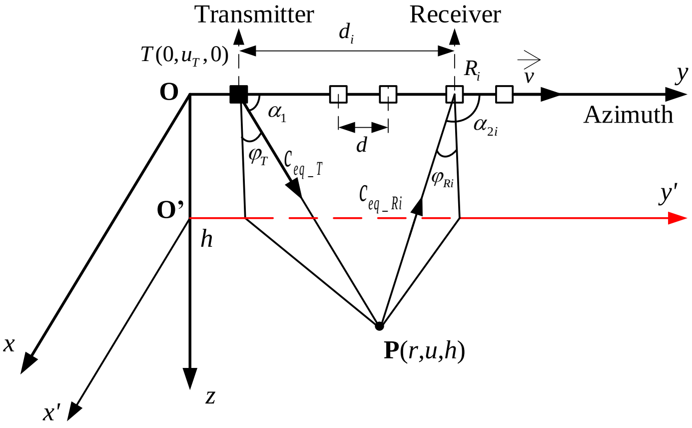


Figure 1. *Three-dimensional geometry model of multi-receiver SAS.*

With the use of ESV, a geometry model of multi-receiver SAS is constructed as figure 1. In this figure, axises Ox, Oy, and Oz represent the ground range dimension, the along-track dimension, and the depth dimension, respectively. The multi-receiver SAS platform moves with the velocity v. The transmitter is at T(0;0;0) with t = 0. The distance between two adjacent receivers is d, and the distance from the transmitter to the ith receiver is d_i. c_{eq_T} and c_{eq_Ri} are the ESVs when emitting to the target at P(r,u,h) and receiving the signal from the target to the ith receiver, respectively, which depend on vertical inclinations φ_T and φ_{Ri} [7].

The sound wave propagation times from the transmitter to the target and from the target to the ith receiver are determined as:

$$\tau_1 = \frac{\sqrt{(u - vt)^2 + r^2 + h^2}}{c_{eq\_T}} \tag{2}$$

$$\tau_{2i} = \frac{v\left(d_i + v\tau_1 - \sqrt{(u - vt)^2 + r^2 + h^2} \times \cos\alpha_1\right) + \sqrt{\Delta_i}}{c_{eq\_Ri}^2 - v^2} \tag{3}$$

where the parameters α_1, α_{2i}, and Δ_i are given by [7].

Owing to the movement of the SAS platform, the Doppler effect appears, and the frequencies of the received signals at P and Ri are different from the transmitted frequency, which are calculated as [8]:

$$f_1 = f_0 \eta_1 = f_0 \frac{c_{eq\_T}}{c_{eq\_T} - v\cos\alpha_1} \tag{4}$$

$$f_{2i} = f_0 \eta_{2i} = f_0 \frac{c_{eq\_Ri} + v\cos\alpha_{2i}}{c_{eq\_Ri}} \tag{5}$$

3. BEAMFORMING SOLUTION FOR MULTI-RECEIVER SAS

Consider the case that the multi-receiver SAS needs to observe the target at point $P_0(r_0, u_0, h_0)$ in an area with a defined SVP. The delay time and frequencies obtained due to the Doppler shift at P_0 and R_i are determined according to the ESVs by the following expressions:

$$\tau_{10} = \frac{\sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2}}{c_{eq\_T0}} \tag{6}$$

$$\tau_{2i0} = \frac{v\left(d_i + v\tau_{10} - \sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2} \times \cos\alpha_{10}\right) + \sqrt{\Delta_{i0}}}{c_{eq\_Ri0}^2 - v^2} \tag{7}$$

$$\begin{aligned} \Delta_{i0} &= v^2\left(d_i + v\tau_{10} - \sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2} \times \cos\alpha_{10}\right)^2 \\ &+ \left(c_{eq\_Ri0}^2 - v^2\right)\begin{pmatrix} (u_0 - vt)^2 + r_0^2 + h_0^2 + (d_{i0} + v\tau_{10})^2 \\ -2\sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2}\,(d_i + v\tau_{10})\cos\alpha_{10} \end{pmatrix} \end{aligned} \tag{8}$$

$$\alpha_{10} = \arccos\left(\frac{u_0 - vt}{\sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2}}\right) \tag{9}$$

$$\alpha_{2i0} = \arccos\left(\frac{u_0 - (d_i + v\tau_{10} + vt)}{\sqrt{\left[u_0 - (d_i + v\tau_{10} + vt)\right]^2 + r_0^2 + h_0^2}}\right) \tag{10}$$

$$\eta_{10} = \frac{c_{eq\_T0}}{c_{eq\_T0} - v\cos\alpha_{10}} \tag{11}$$

$$\eta_{2i0} = \frac{c_{eq\_Ri0} + v\cos\alpha_{2i0}}{c_{eq\_Ri0}} \tag{12}$$

where the equivalent velocities when transmitting to the point $P_0(r_0, u_0, h_0)$ and when receiving from the *i*th receiver are determined according to the SVP and the initial vertical inclinations. The vertical inclinations during transmission and reception change, so the values c_{eq_T0} and c_{eq_Ri0} must also be calculated according to this change. With these changes, the computation load increases significantly during beamforming for multi-receiver SAS.

Based on the survey results on ESV variation in the vertical inclination with SVP from Vietnam’s sea [7], ESV changes very slowly according to the vertical inclination when observing the targets at the sea bottom. As a result, this paper chooses an ESV to replace for c_{eq_T0} and c_{eq_Ri0} when steering the main beam to the desired position determined as:

$$c_{eq\_T0} \approx c_{eq\_Ri0} \approx c_{eq\_av} = \frac{c_{eq\_\min} + c_{eq\_max}}{2} \tag{13}$$

where $c_{eq\_\min}$ and c_{eq_max} are the minimum and maximum values of ESVs, respectively, which correspond to the initial inclinations at the zero value and the maximum value.

From the calculated ESV for the beamforming with SVP from Vietnam's sea, the delay times and the Doppler scale-factors are expressed as:

$$\tau_{10\_pro} = \frac{\sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2}}{c_{eq\_pro}} \tag{14}$$

$$\tau_{2i0\_pro} = \frac{v\left(d_i + v\tau_{10\_pro} - \sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2} \times \cos\alpha_{10}\right) + \sqrt{\Delta_{i0\_pro}}}{c_{eq\_pro}^2 - v^2} \tag{15}$$

$$\begin{aligned}\Delta_{i0\_pro} &= v^2\left(d_i + v\tau_{10\_pro} - \sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2} \times \cos\alpha_{10}\right)^2 \\ &+ \left(c_{eq\_pro}^2 - v^2\right)\begin{pmatrix}(u_0 - vt)^2 + r_0^2 + h_0^2 + \left(d_{i0} + v\tau_{10\_pro}\right)^2 \\ -2\sqrt{(u_0 - vt)^2 + r_0^2 + h_0^2}\left(d_i + v\tau_{10\_pro}\right)\cos\alpha_{10}\end{pmatrix}\end{aligned} \tag{16}$$

$$\eta_{10\_pro} = \frac{c_{eq\_pro}}{c_{eq\_pro} - v\cos\alpha_{10}} \tag{17}$$

$$\eta_{2i0\_pro} = \frac{c_{eq\_pro} + v\cos\alpha_{2i0}}{c_{eq\_pro}} \tag{18}$$

From the selection of ESV equalling the average value of the maximum ESV and the minimum ESV, the numbers of calculations for beamforming by the proposed solution decrease compared with the proposed solution calculating the delay time with formulas (6-12).

With the proposed solution, the phase distribution when steering the main beam to the target at $P_0(r_0, u_0, h_0)$ is determined as:

$$\psi_i(t, r_0, u_0, h_0) = 2\pi\left(f_0\eta_{10\_pro}\tau_{10\_pro} + f_0\eta_{2i0\_pro}\tau_{2i0\_pro}\right) \tag{19}$$

Echo signals at receivers in each ping are coherently combined by the expression:

$$AF_0(y, r_0, u_0, h_0) = \sum_{m=1}^{M}\sum_{i=1}^{N} s_i(t)\exp\left(j\psi_i(t, r_0, u_0, h_0)\right) \tag{20}$$

where $s_i(t)$ is the received signal at the *i*th receiver in the *m*th ping at time *t* ($y=vt$), *M* is the number of pings for coherently processing.

4. SIMULATIONS, RESULTS, AND DISCUSSIONS

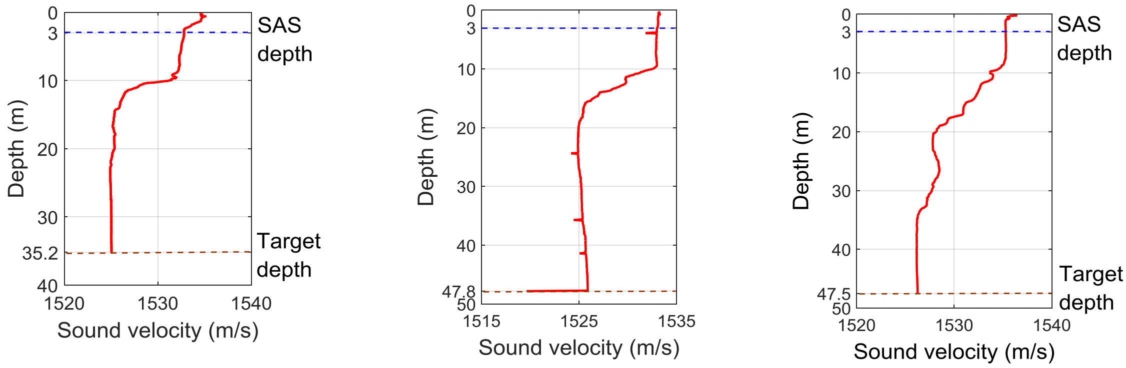
4.1. Simulations and the Results

To demonstrate the validation and the effectiveness of the proposed solution, this section considers a multi-receiver SAS system with configuration as in table 1. In this table, the elements are arranged densely without gaps, the platform velocity, the number of receivers, and the pulse repetition interval are chosen to avoid grating lobes [1].

Table 1. *Parameters of multi-receiver SAS for beamforming.*

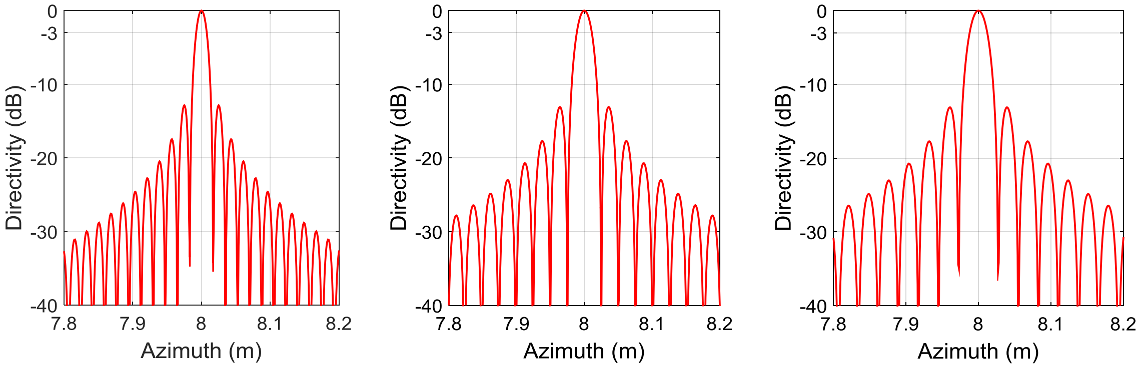
Parameter	**Value**	**Unit**
Carrier frequency (f_c)	100	kHz
Platform velocity (v)	2	m/s
Distance from transmitter to the first receiver (d_1)	0.03	m
Distance between two adjacent elements (d)	0.02	m
The number of receivers (N)	64	element
Pulse repetition interval (T_l)	0.25	s
The number of pings (M)	30	

The paper considers SVPs obtained from Vietnam's Sea at geographical coordinates (16°59'04"N, 107°20'05"E) and (17°03'42"N, 107°26'28' 'E) on April 12, 2021, and at (17°03'33"N, 107°27'04"E) on April 15, 2021. These SVPs were received by sound velocity profiler SWIFT SVP of Valeport Ltd and shown in figure 2. Assume that the three targets need to be steered at positions (10 m; 8 m; 32.2 m), (20 m; 8 m; 44.8 m), (30 m; 8 m; 44.5 m) in the three-dimensional coordinate system (Oxyz) corresponding to the three above SVPs. With the number of pings 30, the point targets are in the main beam of each receiver element.



(a) *(b)* *(c)*

Figure 2. *SVPs obtained from Vietnam's Sea at geographical coordinates: a) (16°59'04"N, 107°20'05"E); b) (17°03'42"N, 107°26'28"E); c) (17°03'33"N, 107°27'04"E).*



(a) *(b)* *(c)*

Figure 3. *Beam patterns with SVPs from Vietnam's sea for steering the targets at positions: a) (10 m; 8 m; 32.2 m), b) (20 m; 8 m; 44.8 m), c) (30 m; 8 m; 44.5 m).*

According to the survey results of equivalent sound velocity in [7], the value of c_{eq} is nearly unchanged in the vertical inclination φ_0. Therefore, it is possible to choose an average value for processing. This section selects the sound velocity value for beamforming, which is the average value of the minimum value at the vertical inclination of 0° and the maximum value at the vertical inclination 80°. With the selection, the c_{eq} values for 3 target points at (10 m; 8 m; 32.2 m), (20 m; 8 m; 44.8 m), (30 m; 8 m; 44, 5 m) corresponding to 3 SVPs in figure 2 are 1526.960 m/s, 1527.019 m/s, 1529.300 m/s, respectively. The beam patterns obtained using MATLAB software from the above three points are shown in figure 3.

4.2. Discussions

Figure 3 shows that the main beams steer at desirable positions with azimuth deviations equalling approximately zero (the processed signals are in phase) when the step in azimuth dimension is 1 mm. With the average value of ESV from the proposed solution, the phase distribution is generated almost the phase distribution determined from the sum of sound wave propagation time into straight lines, where the sound velocity is unchanged. Compared with this conventional solution, the proposed solution provides the same efficiency of position error while decreasing computation time thanks to the reduction of the calculation numbers of ESV for each SVP. To compare computation load from the two solutions, this study determines the calculation time of phase distribution for steering the main beam to the desired position on a laptop with an Intel i7-1065G7 processor, and 8 GB of RAM. The average values of ten calculation times for three positions are shown in table 2.

Table 2. *Time for calculating phase distribution.*

Positions of targets	*Conventional*	*Proposed*
(10 m; 8 m; 32,2 m)	0.9358 (s)	0.0431 (s)
(20 m; 8 m; 44,8 m)	1.1333 (s)	0.0454 (s)
(30 m; 8 m; 44,5 m)	1.1816 (s)	0.0447 (s)

Table 2 shows that with the 64-element receiver array and 30 pings, the time values for determining the phase distribution from the proposed solution are 20 times smaller than that from the conventional solution for three target positions corresponding to three SVPs at Vietnam's sea. This improvement of computation load is achieved because the proposed solution only requires two calculations for ESV (minimum and maximum value), whereas the conventional solution needs 2×30×64=38400 calculations for ESV (or delay time). From table 2, the time value for determining the phase distribution to steer the main beam to the second and third target is approximately the same and larger than that to observe the first target because the second and third targets are at approximate depths. Besides, their depths are also larger compared with the depth of the first target. With the increase of depth, the number of calculations for determining ESV rises. Therefore, the proposed solution improves the efficiency in reducing the calculation time of the phase distribution when observing targets at large depths. In addition, the proposed solution can be applied not only for SAS but also for other sonars such as sectorscan sonars, sidescan sonars, and minehunting sonar systems.

5. CONCLUSIONS

Based on the average value of ESV, this paper has proposed a beamforming solution for multi-receiver SAS with SVPs from Vietnam's sea. The calculation results have shown that the proposed solution generated a phase distribution, which could steer the main beam to desirable positions similar to the conventional solution. Moreover, the proposed solution has reduced the computation load compared with the conventional solution determining the delay time according to the change of sound velocity. The effectiveness of the proposed solution has been demonstrated by calculation results with SVPs obtained at the positions in Vietnam's sea.

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TÓM TẮT

Nghiên cứu giải pháp tổng hợp búp sóng cho sonar mặt mở tổng hợp nhiều máy thu sử dụng xung CW với các dữ liệu về vận tốc truyền âm ở biển Việt Nam

Bài báo này đề xuất giải pháp tổng hợp búp sóng cho sonar mặt mở tổng hợp nhiều máy thu sử dụng xung CW dựa trên giá trị trung bình của vận tốc truyền âm tương đương khi xét đến sự thay đổi của vận tốc truyền âm theo độ sâu. Với giải pháp đề xuất, có thể hướng búp sóng chính của giản đồ hướng tổng hợp đến mục tiêu cần quan sát. Giải pháp đề xuất còn giảm được thời gian tính toán phân bố pha so với giải pháp tính thời gian trễ truyền thống bằng cách chia quãng đường truyền sóng thành các đoạn thẳng với vận tốc truyền âm không đổi. Hiệu quả của giải pháp đề xuất được xác thực và minh chứng bằng các kết quả tính toán giản đồ hướng và thời gian xác định phân bố pha với các bản ghi vận tốc truyền âm (SVPs) ở biển Việt Nam.

Từ khoá: Sonar mặt mở tổng hợp; Tổng hợp búp sóng; Vận tốc truyền âm tương đương.