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Experimental Study of Backscattered Underwater Signals from Multiple Scatterers

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Abstract

Backscattered underwater signals from multiple scatterers contain information regarding resolvable spatial distribution of scatterers. This experimental study describes the spectral characteristics of backscattered signal from multiple scatterers, which are regularly or randomly spaced, in terms of their amplitude and phase and a proper signal analysis that will eventually provide scatterer spacing estimation. Air-filled tubes suspended in water, steel balls and plastic tubes buried in the sediment are the multiple scatterers. The cepstrum and the spectral autocorrelation (SAC) methods were used to estimate the scatterer spacing from the backscattered signals. It was found that the SAC method could be improved by employing singular value decomposition (SVD) to extract the effective rank for the spectral components. Unlike the conventional method of estimating the density of scatterers within the insonified volume of water, this type of estimation method would provide better understanding of the spatial distribution of scatterers in the ocean.

Keywords: *Multiple scatterers, Backscattered underwater signal, Spatial distribution spectrum, Phase spectrum, Scatterer spacing*

I. Introduction

The spatial distribution of multiple scatterers in the sea, such as bubbles, fishes, planktons, and roughness of boundaries of the sea surface and floor has been subjects of research topics among underwater acoustic community[1-7] In naval applications, dispersed scatterers in the ocean volume can cause echoes that may be mistaken for false targets. In fisheries research, the spatial distribution of scatterers is the major measurement for assessing the abundance of many fish stocks. Thus, there are both commercial and military needs for a complete understanding of the distribution of scatterers[8].

In general, information on the distribution of scatterers is based on the level of the backscattering strength from a fixed insonified volume or area. The sonar echo integration technique is a standard use to determine the density of scatterers of the volume or area, because the intensity of the scattering is a function of the density of the scatterers. The integrated backscattering intensity is a useful parameter to find distribution of scatterers but it is only the quantitative value of backscattered energy that is the ratio of the intensity of the sound scattered to the incident wave. The backscattered sound intensity depends on the frequency of the incident sound; the size, the shape and the orientation of the scatterer with respect to the transducer (source-receiver)[9]. It can accurately provide relative densities but absolute densities require complex calibration of the system. Most fish finding sonars are neglecting multiple scattering and phase difference between scatterers or fishes. They are rather simply adding together the scattering cross sections for the individual scatterer to estimate a biological abundance in quantitative way but not in qualitative way[10-11].

Therefore a qualitative estimation of the number of scatterers in volume or area would provide better understanding of the spatial distribution of scatterers in the ocean. In order to calculate distribution or density of

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Table 1. Experimental parameters used to collect the scatterer signals.

Exp.	Scatterer and dimension		Transducer	Pulse length	Sampling freq.
1, 2	PVC tube	ID* 1.2 cm	126 kHz	0.04, 0.08, 0.16, 0.30, 0.60 ms	500 kHz
		OD* 1.6 cm 1m long			
3	Solid steel ball D* 3.2cm		50 kHz	0.1 ~ 0.4 ms	400 kHz
4	Plastic tube	ID* 4 cm	50 kHz	0.1 ~ 0.4 ms	400 kHz
		OD* 4.8 cm 30cm long			

ID: inner diameter, OD: outer diameter, D: diameter

scatterers, intense signal processing on the backscattered signal are required. For example, signal processing with the Cepstrum and SAC (Spectral Auto Correlation) are commonly used in Ultrasonic tissue characterization based on the estimation of scatterer spacing[12-15]. The most important part of the signal processing is to estimate the average distance between multiple scatterers using the amplitude or the phase information of the spectrum of the backscattered signals [14].

The purpose of this study is to describe the spectral characteristics of backs

cattered signal from multiple scatterers in terms of their amplitude and phase with a proper signal analysis that will eventually provide scatterer spacing estimation. For that, high frequency (50 kHz, 126 kHz) backscattered signals were obtained in a tank experiment from multiple scatterers of known spacing or numbers in a unit volume, like cylindrical tubes, pipes and spherical steel balls buried in the sediment.

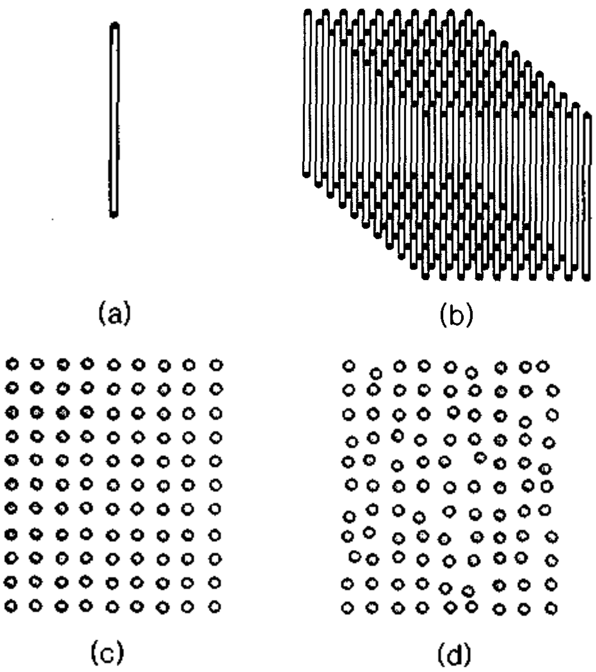


Figure 1. Experimental scatterers design for the measurements of backscattered signals: (a) A rubber capped air filled tube, (b) Arrayed cylindrical tubes, (c) Regularly spaced ACT and (d) Randomly spaced ACT viewed in horizontal plane.

II. Description of the Experiments

Backscattered signals were obtained in a tank experiment

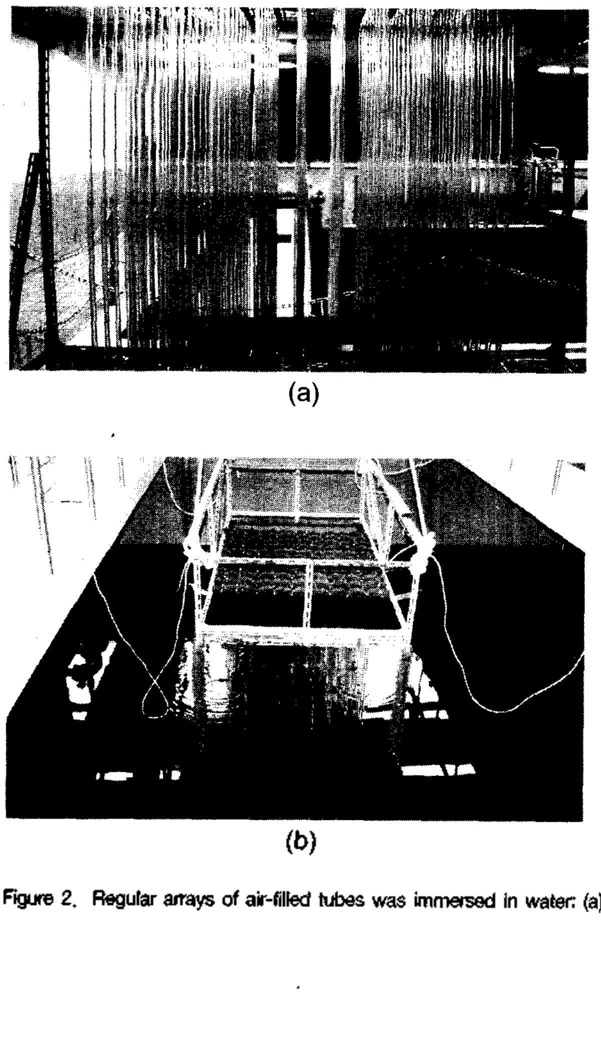


Figure 2. Regular arrays of air-filled tubes was immersed in water: (a)

Table 2. Summary of estimation results.

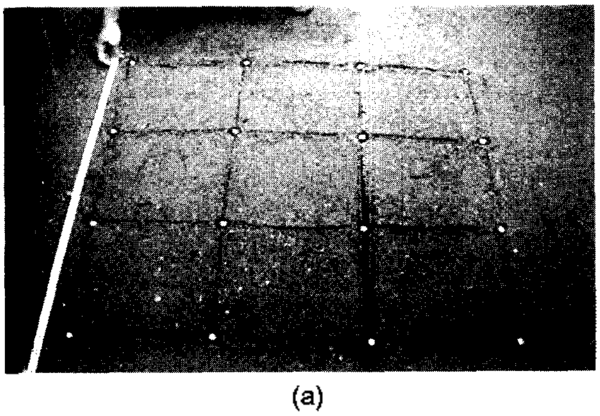
Experiments			Scatterer Spacing	Estimated Spacing
1	PVC tube	Regular	0.1 m	0.120 m[1] 0.098 m[2]
2		Random	0.1 0.1 m $\pm\Delta s$ $0 \le \Delta s \le 0.1m$	0.087 m
3	Steel ball		0.246* m	0.256 m
4	Plastic tube		0.246* m	0.248 m

*0.3m × cos35°=0.246m, 1: cepstrum, 2: SAC function

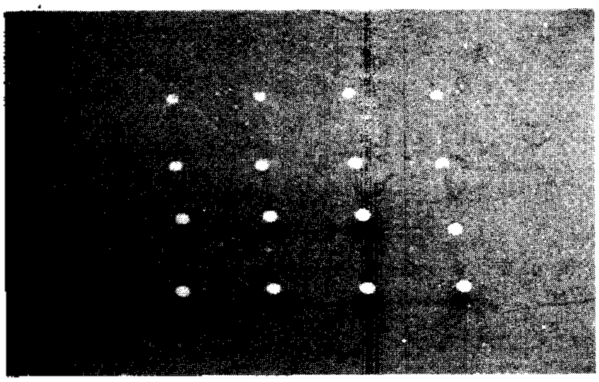
from suspended array of cylindrical tubes, either regularly or randomly spaced, and regularly spaced steel balls and plastic tubes buried in sand (Figs. 1-3).

The experiments were performed in a water tank with a 0.5m-thick sandy bottom at the Ocean Acoustics Laboratory (OAL) in Hanyang University (Fig. 4). The tank has the following dimensions: 5 m length × 5 m width × 5 m depth. No four sides are parallel in consideration of effects of multipath interference and the volume of the tank is to about 125 m^3.

In the first two experiments, regularly spaced and randomly spaced arrays of air-filled cylindrical PVC tubes were suspended in water tank (Table 1). A 126 kHz transducer (HY-126) was located at depth of 3.1 m pointing to the center of the ACT to obtain backscattered signals of various pulse lengths 0.04, 0.08, 0.16, 0.30, 0.60 ms at incident angles from −30° to 30°. Source level was 159 dB re 1 μPa at 1 m and receiving sensitivity was −167 dB re 1V/1μPa. The incident wave was a CW pulses, generated with a waveform generator (Lecroy LW410A). The signal was then amplified by power amplifier (B&K model 2610) and sent to the transducer. The voltage and current from the power amplifier were monitored by oscilloscope. The signals of the backscattered sounds were acquired with 12-bit A/D conversion using appropriate time gate (10 ms) with gain settings controlled by the computer. The 3 dB beam width of 126 kHz transducer was 12°. Fifty pings separated by 1.5 second intervals were averaged in the time domain. These procedures were repeated for randomly spaced ACT. Figure 5 shows the experimental layout for measurements of backscattered signal from the arrayed

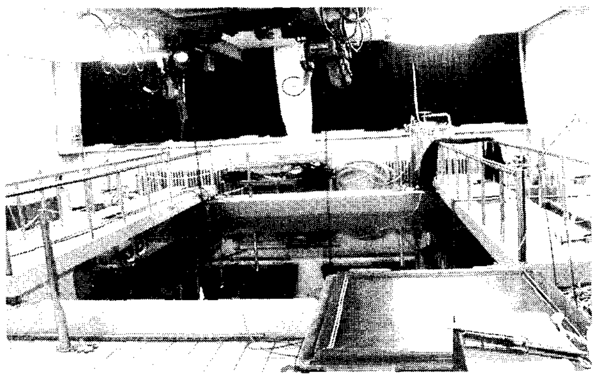


(a)

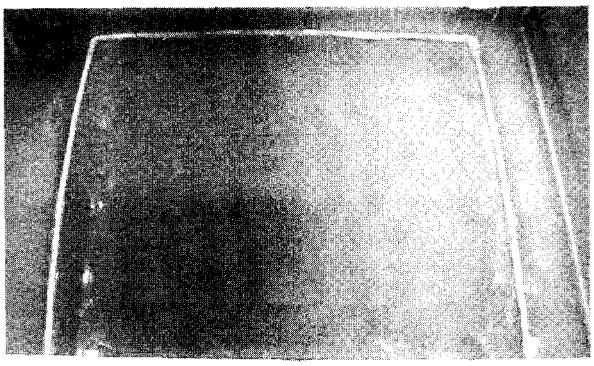


(b)

Figure 3. Solid steel balls or plastic tubes were buried in sediment: (a) solid steel balls and (b) plastic tubes.



(a)



(b)

Figure 4. (a) The water tank: 5 m×5 m×5 m and (b) 4m×4 m× 0.5 m sandy bottom at the Ocean Acoustics Laboratory (OAL) in Hanyang University.

cylindrical tubes (ACT). The sound velocity profile was measured with a CTD and it showed the sound velocity was constant of 1434 m/s.

In the second two experiments, 16 solid steel balls and 16 air-filled plastic tubes were buried below the water-sediment interface (Table 1). In these experiments, a 50 kHz transducer (TC-2116) was used with various pulse lengths (0.1, 0.2, 0.3, 0.4 ms) and the grazing angle was fixed at 35° (Fig. 6). The experiments were aimed at detecting solid steel balls and air-filled plastic tubes buried under about 5cm of sand, by using a focused transducer with a center frequency of 50 kHz placed at a height of 1m above the bottom. Also, in terms of the water-sediment interface, diffused signals obtained were used to estimate scatterer spacing. Source level was 170.5 dB re 1 μPa at 1 m and receiving sensitivity was −177.2 dB re 1V/1μPa. The beam width of 50 kHz transducer was 14.6° with the incident CW pulses, separated by 1.0 second intervals backscattered signals were averaged in the time domain for each pulse length. The average sound velocity measured with a CTD was 1483 m/s and water temperature is 20.3°. The sediments have a mean grain size (Mz) of 0.5 ϕ (coarse sand). Scatterers dimensions for each experimental setup are given in Table 1.

III. Data Analysis

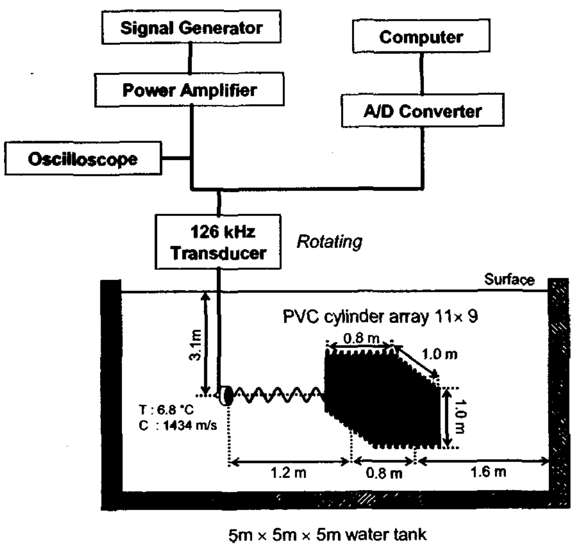


Figure 5. Experimental configurations for the measurements of backscattered signals for regularly spaced and randomly spaced arrays of air-filled cylindrical PVC tubes.

Parameters needed to describe scatterers characteristics can be extracted from the processed backscattered signal, such as integrated backscatter strength, attenuation, reflection coefficients, scatterers distribution, and scatterer spacing. In this chapter, the integrated backscatter and scatterer spacing are introduced.

3.1. The Integrated Backscattering Intensity

Echo integration is often used as a means to estimate scatterers density and distribution when there exists multiple scatterers within the sonar beam. In other word, the integrated backscattering intensity is called Time integral pressure squared [11].

The volume scattering coefficient is a measure of the backscattering from particles and inhomogenities in the volume. Consider a spherically spreading medium of constant sound velocity (c) with volume absorption coefficient α (dB/m). The time integral pressure squared of the gated volume (subscript GV) within opening time $t_2 - t_1$ is a useful measure of the scattering when echoes overlap

Scattering measurements give the time integral pressure squared (TIPS) of the gated volume. The *volume scattering coefficient* $s_V(f)$ is

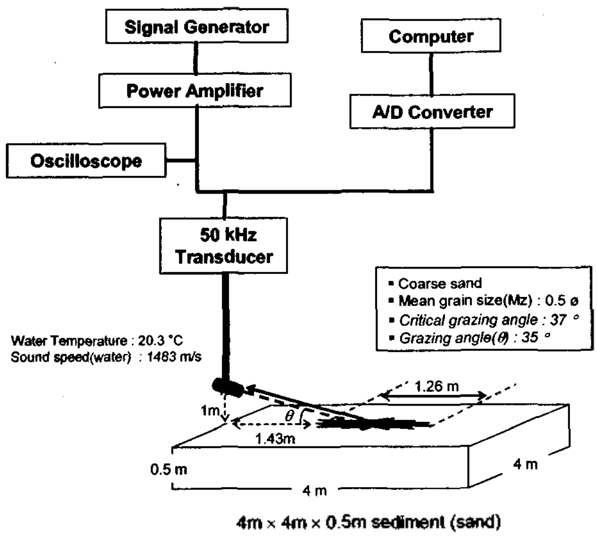


Figure 6. Experimental configurations for the measurements of backscattered signals for 16 solid steel balls and 16 air-filled plastic tubes.

$$s_V(f) \approx 2\frac{[tips]_{GV} R^2 \; 10^{\alpha R/5}}{\psi_D [tips]_0 (t_2 - t_1) c R_0^2} \tag{1}$$

where

$[tips]_{GV}$: The *gated time integral pressure squared of the volume reverberation* (GV)

$[tips]_0$: The time integral pressure squared of the source pressure $p_0(t)$

P_0 : The RMS source pressure at R_0.

R : The mean distance between sound source and the scatterer

ψ_D : Integrated Beam Pattern

Also assume that the multiple scatterers are uniformly distributed with density n_b in the gated volume,

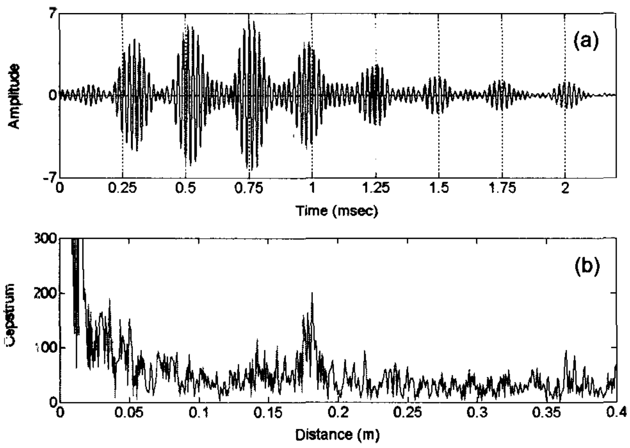


Figure 7. The scattering response of the regular spaced simple scatters: (a) shows the time series of backscattered signal separated by time $\tau = 0.25\,ms$; sampling interval is $2.5\,\mu s$ and (b) Dominant peak represented at $d = 0.185\ m$ in cepstrum.

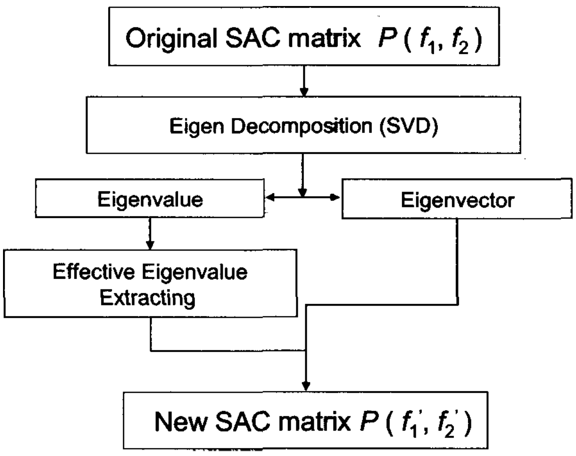


Figure 8. The flow chart of signal processing for decompose of SAC matrix with the SVD method.

$$n_b = number\ of\ scattering\ objects / m^3 \tag{2}$$

The density of scatterers and the mean square backscattering cross section define the *volume backscattering coefficient*:

$$s_V(f) = n_b < \sigma_{bs} > \tag{3}$$

where both s_V and $< \sigma_{bs} >$ depend on frequency.

Finally, in terms of Eq. (1) and Eq. (3), The volume backscattering strength when many scatterers are present in a fixed insonified volume or area is given as

$$S_V = 10 \log_{10}[(s_V)/(s_{V,ref})]\ \text{dB} \tag{4}$$

It will be presented next chapter the measured value (Eq.1) and compare it to the expected value (Eq.3).

3.2. Estimation of Scatterer Spacing

The scatterer spacing characteristics are present in both the amplitude and the phase of the spectrum. Therefore, the cepstrum (amplitude spectrum) and the spectral autocorrelation (both amplitude spectrum and phase spectrum) introduced to develop a robust algorithm for the estimation of the scatterer spacing[12].

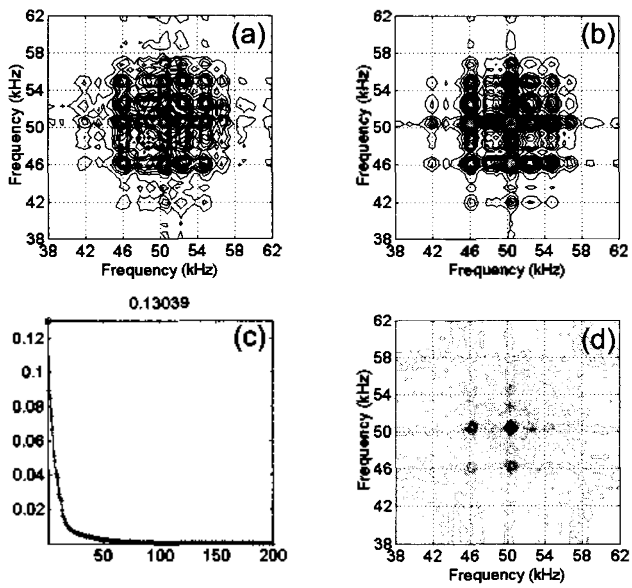


Figure 9. (a) The original SAC matrix UwV^T, (b) The new SAC matrix $Uw_{new}V^T$ that extracted effective element of w, (c) Rank of Eigenvalue and (d) Residual SAC matrix.

The cepstrum is defined as

$$\log\left|Y(f)\right|^2 =$$

$$\log\left|X(f)\right|^2 + \log\left|H(f)\right|^2 + 2\log\left|1 + e^{-i2\pi f(2d/c)}\right| \qquad (5)$$

The last term is periodic with period equal to $c/2d$. Upon Fourier transformation as the final step toward computing the cepstrum, this periodicity will manifest itself as a peak at $t = 2d/c$. Assuming that the transfer function, $X(f)$, and the frequency dependent backscatterer, $H(f)$, do not vary dramatically over changes of frequency on the order of $c/2d$, their contributions to the cepstrum will be confined to times much smaller than $2d/c$. The scatterer spacing is computed from the location (Δt) of the dominant peak in the cepstrum estimated from the power spectrum (Fig. 7).

$$d = \frac{1}{2}c\Delta t \qquad (6)$$

While the cepstrum can be used to characterize the scatterer spacing, it relies only on the amplitude spectrum, which is directly affected by the system response and diffuse scattered energy[12]. The SAC function, however, uses information in the phase spectrum, which results in local maxima in the bifrequency plane where the mean contributions of the diffuse scatterer energy are zero. As a result, the SAC function provides a more robust estimate than the power spectrum for scatterer spacing in the presence of diffuse scattering.

The spectral correlation peaks in bifrequency domain show that the diagonal component ($f_1 = f_2$) is equivalent to the PSD, and the off-diagonal terms are due to the decreased amplitude variation.

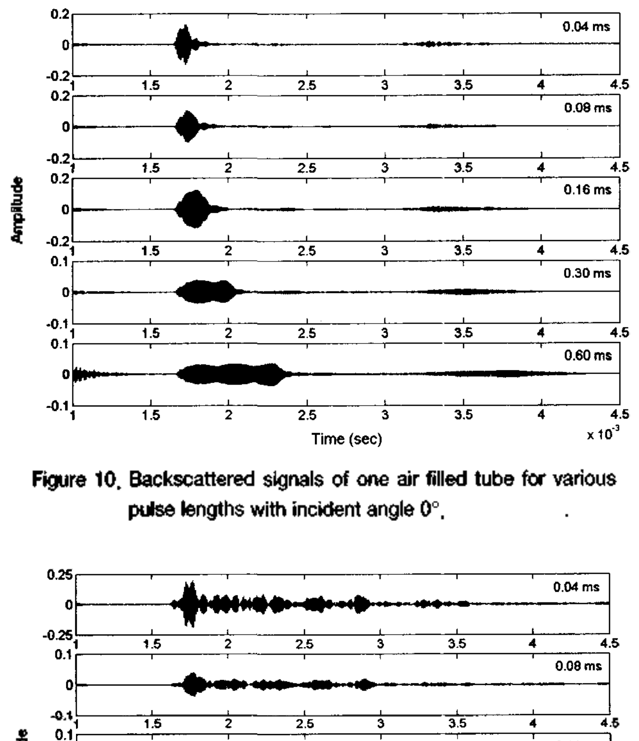


Figure 10. Backscattered signals of one air filled tube for various pulse lengths with incident angle 0°.

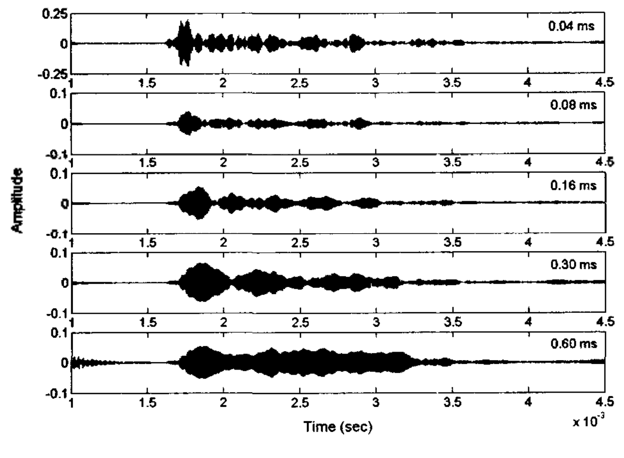


Figure 11. Backscattered signals of ACT for various pulse lengths with incident angle 0°.

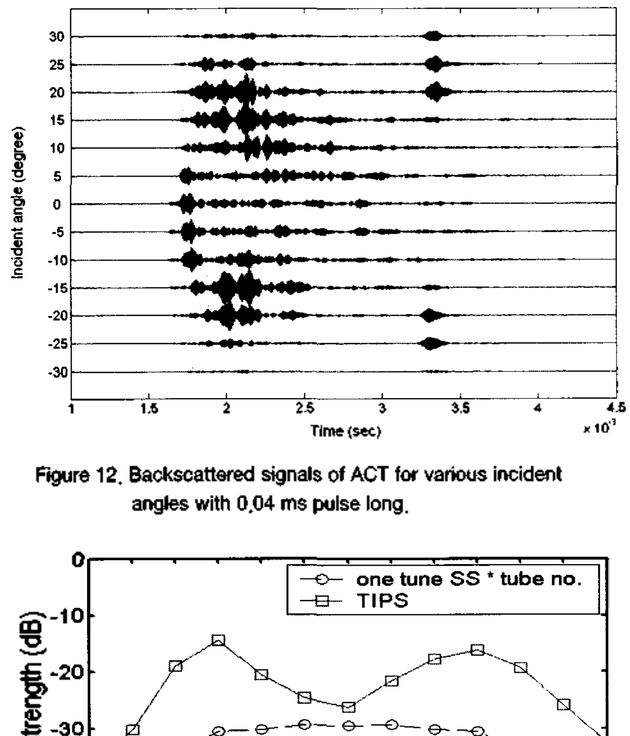


Figure 12. Backscattered signals of ACT for various incident angles with 0.04 ms pulse long.

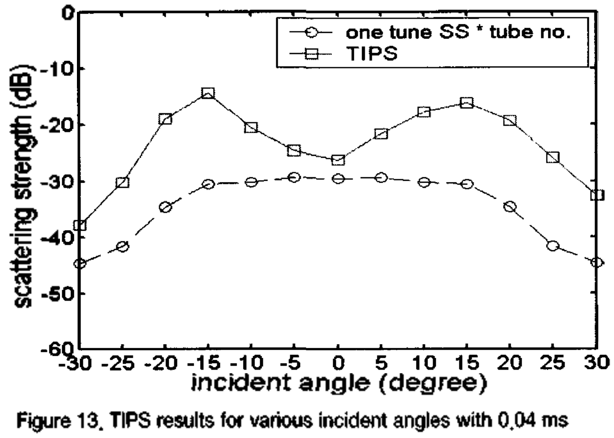


Figure 13. TIPS results for various incident angles with 0.04 ms pulse long. The circles on the dashed line corresponded to the values that were calculated by multiplying a single scattering strength by the total number of scatterers within the insonified beam field.

The SAC function is defined over a bifrequency plane by

$$S_T(f_1,f_2;t) = H(f_1;t)H^*(f_2;t) \cdot \left(E\left[\sum_{n=1}^{N_S'}\sum_{m=1}^{N_S'} A_n(f_1)A_m^*(f_2)e^{-j2\pi\Delta(f_1 n - f_2 m)}\right] + \sum_{n=1}^{N_D'} E\left[V_n(f_1)V_m^*(f_2)\right]\delta(f_1-f_2) \right) \tag{7}$$

where f is frequency, t is a time axis, $H(f)$ is the Fourier transforms of time varying system response function and $A_n(f)$ and $V_n(f)$ denote the frequency dependent scattering strength of regular and diffuse scatterer, respectively.

We observe that the periodicity manifests itself in both cepstrum (Δt) and spectral autocorrelation (Δf). That is used to compute the scatterer spacing. For the SAC

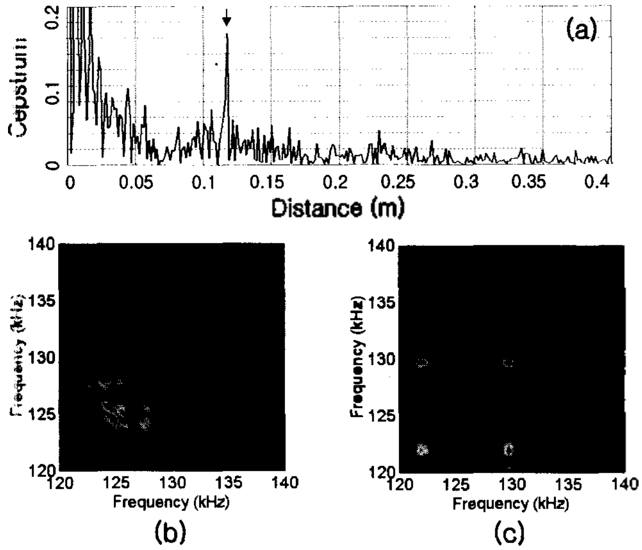


Figure 14. Estimation of the scatterer spacing for the regularly spaced PVC tubes: (a) Cepstrum, (b) spectral autocorrelation function (SAC) and (c) SAC after effective rank estimation with SVD.

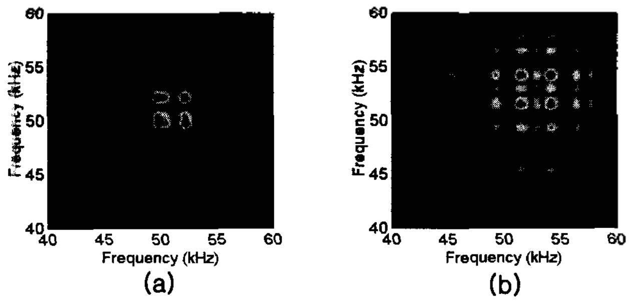


Figure 15. SAC functions are effective rank estimation using singular value decomposition: (a) Regularly spaced steel balls and (b) regularly spaced air-filled plastic tubes, buried in a sandy bottom.

function, the location of the dominant peak among the off-diagonal spectral components at (f_1, f_2), corresponds to a frequency difference $(\Delta f = f_1 - f_2)$ that is used to compute the scatterer spacing

$$d = \frac{c}{2\Delta f}\ , \tag{8}$$

In order to obtain clearer peaks in the SAC matrix, rank-estimation by singular value decomposition (SVD) was used. Using the SVD, we can determine the rank of SAC matrix, obtain an optimal rank to the matrix[17]. Our interest in the SVD, is extracting Eigenvalue for scatterer spacing. The SVD reduced the SAC matrix to the form UwV^T , where w is diagonal. Effective element of w was extracted and the new SAC approximation $Uw_{\text{new}}V^T$ was formed (Figs. 8-9).

IV. Experimental Results

4.1. The Integrated Backscattering Intensity

The results of calculated scattering strengths were presented using the integrated backscattering intensity. An air filled PVC tube was suspended vertically at 3.75 m water depth by cables. The scattering strength of a single PVC tube was measured as about -49.7 dB at pulse length 0.04 ms. Figure 13 shows the possible effects of scattering strength changes with incident angles. The changes in scattering strength may be due to the incident angle, rather than volume change or number of scatterers in beam filed. In Figure 13, solid line (square symbol) represents the scattering strength. The circles on the dashed line correspond to the values that were calculated by multiplying a single scattering strength by the total number of scatterers within the insonified beam field.

The number of scatterers existing within the beam field when the incident angles varies turns out to be not changed for three incident angles of 0, 5, and 10 degree. However, Measured scattering strength varied from −26.3 to 17.8 dB. Therefore, a simple addition of the scattering cross section to obtain a total scattering strength, which has been a common practice in estimating the biological abundance (e. q. fish, plankton etc.) would cause mis-judgement. These results clearly demonstrated the necessity for intense signal processing, that is, scatterer spacing.

4.2. Estimation of the Scatterer Spacing

The signals were analyzed using the cepstrum and SAC methods and experimental results presented. Figure 14 illustrates the effectiveness of three different methods used to estimate the scatterer spacing for the regularly spaced tubes immersed in water. The cepstrum method (Fig. 14(a)) clearly shows a 0.12m scatterer spacing. However, the actual spacing of the scatterers in the water was 0.1m. In order to estimate scatterer spacing from the spectral autocorrelation function, it is necessary to identify a regular grid of spectral peaks. However, a contour plot of the SAC function (Fig. 14(b)) shows rather diffuse off-diagonal components, which hinder estimation of the spacing.

In order to obtain clearer peaks in the SAC, rank-estimation by singular value decomposition was used. The SVD reduced the SAC matrix to the form UwV^T, where w is diagonal. Small elements of w were set to zero and the new SAC approximation $Uw_{\text{new}}V^T$ was formed, as shown in Figure 14(c). Through SAC results suppress the interference of dominant spectral components are clear and sharp such that locations of the off-diagonal peak at (129.7, 122.4) kHz which corresponds to Δf =7.3 kHz was selected. In the new figure, a regular grid of four peaks with a spacing of Δf =7.3 kHz is clearly visible. This corresponds to a scatterer spacing of 0.098m, very close to the measured value of 0.1m.The same method was applied to each set of signals, including the randomly spaced array of tubes, and buried regular arrays of steel balls and plastic tubes. In each case, the pulse length giving the sharpest peak in the cepstrum was selected for processing with the SAC and SVD. It was found that a sharper SAC function could be estimated using rank estimation by singular value decomposition. The resulting estimates of scatterer spacing were better than those derived using cepstrum techniques.

The spacing estimates for each case are shown in the Table 2. Estimates derived by SVD rank-estimation on the SAC function were better than those derived using the cepstrum method or the original SAC function.

V. Summary and Conclusions

Laboratory study of the scattering of sound by multiple scatterers, either in arrayed shape in water or buried in sediment, was carried out in an effort to estimate the scatterer spacing for a complete understanding of the distribution scatterers. The signals were analyzed using the cepstrum technique and the SAC function. It was found that a sharper SAC function could be estimated by using rank estimation in singular value decomposition (SVD) method. The resulting estimates of scatterer spacing were better than those derived using cepstrum techniques. Furthermore, it was shown that better spacing estimates could be achieved by using singular value decomposition and effective rank estimation to refine the SAC.

Unlike the conventional method of estimating the density of scatterers within the insonified volume of water, the estimation of scatterer spacing may give a better estimation of the number of scatterers.

This type of estimation method in underwater acoustics can be applied to a wide variety of real object: fishes, phytoplanktons, zooplankton, and marine organism in sea volume. Therefore a qualitative estimation of the scatterers distribution would provide better understanding of the ocean boundaries and volume.

Acknowledgement

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[Profile]

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