Sub-Bottom Synthetic Aperture Sonar in Robust Circumstances

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***Abstract*— In Kanda Bay of Fukuoka of Japan, 2,996 pieces of chemical ammunitions was detected in the exploration until 2012.**

Therefore, we have developed sub-bottom synthetic aperture sonar for high resolution at low frequency to explore the targets of the deposited layer.

Sonar can be mounted on a small ship under the robust circumstances of environment.

We have considered next five issues; refraction at the deposited layer, the frequent velocity change due to tide and wave for small ships, also frequent movement of sensors, week signals in the deposited layer, and flexibility in offline processing, and have developed the solutions.

We have carried out the detection test of targets buried in the seabed sediments at Kanda Bay in July and September 2012, and we report the processing method and the result in this paper.

Keywords—synthetic aperture sonar, sea sediment, deposited layer

I. Introduction

In Kanda Bay of Fukuoka of Japan, chemical ammunitions were discovered in 2000 for the first time, 2,996 pieces of them were detected by the end of 2012 in the exploration.

It is estimated that there are a large number of chemical ammunitions undiscovered still on the Japanese coast. It is harmful to the human body, if the shell is damaged and chemical ingredients are leaked.

Magnetic survey has been used to find ammunitions, since they are buried in the seabed sediments, and no other practical survey method is found until now.

It detects various objects which contain magnetism including tires or bicycles, etc.

If we can detect them with their approximate shape and dimensions by using sonar, it is possible to reduce the time and efforts significantly.

Therefore, we have developed SBSAS (Sub-bottom synthetic aperture sonar) that can be mounted on the broadside of a small ship. We have carried out the detection test of targets buried in the seabed sediments at Kanda Bay in July and September 2012, and we report the processing method and the result in this paper.

There are development examples [1][2] of synthetic aperture sonar to detect buried mines, in order to avoid the explosion of the mine, detection distance is rather long. Because there is no need for SBSAS to avoid an explosion, it can be realized in the short detection distance within about 50m.

Fig.1 Chemical ammunition found in Kanda Bay

II. Test Equipment

Wet end of the SBSAS is shown in Fig.2.

Transmitting system transmits LFM wave at 15 kHz center frequency of 10 kHz band width, 1ms pulse width, and 10Hz pulse repetition frequency.

Reception system consists of horizontal 5ch × vertical 3ch receivers, in which horizontal spacing is 10cm.

Navigation system consists of RTKGPS (Trimble SKS851), Optical Gyro (CD/L MiniPOS2), and DVL (LinkQuest NavQuest600 Micro) for use in moving compensation.

Test targets are the five spherical buoys of plastic with a diameter of 24cm filled with water, and setting depth below the seabed of each target is 1m, 2m, 3m, 3.7m and 4.7m respectively. (Fig.3)

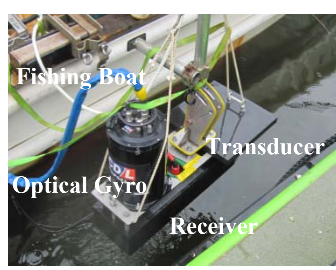

Fig.2 SBSAS wet end

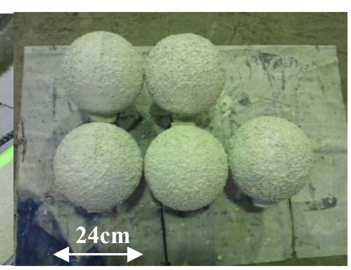

Fig.3 Test targets

III. Problems to be solved

In the SBSAS There are five issues to be solved.

(a) For sound speed in seabed sediments is faster than that in sea water, and, it is necessary to compensate the influence in the synthetic aperture processing.

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(Sound speed compensation)

(b) The small ship velocity is difficult to keep constant. Since the receiver's spacing of synthetic aperture varies, it is necessary to compensate the velocity. (Ships velocity compensation)

(c) Sensor motion is required to be compensated by using the motion data obtained from the external navigation system. (Motion compensation)

(d) Since the signal strength in the seabed sediments is weak, the target visibility is poor. A method of improving the visibility is required. (Visibility improvement)

(e) Synthetic aperture processing is desirable to be able to online on board. But, since the tunable acoustic parameters (sound speed, ship velocity, sensor motion, etc.) are so many, it is necessary to be processed by changing the condition offline in various ways.

IV. SOLUTIONS

We use the CS (Chirp Scaling) method to synthetic aperture processing [3]. CS can be realized only by multiplication with the phase function and fast Fourier transform (FFT). Based on the CS method, we have done compensation processing.

A. Sound speed compensation

Since the sound speed in seabed sediment faster than that in sea water, target in the seabed sediment looks like if it were in the position shallower than actual.

A phenomenon where the focus is not fit to the object, image blurring occurs. To overcome this, we compensate the sound speed, utilizing the fact that, regardless of the azimuth angle, the ratio of apparent distance and actual distance is determined only by underwater sound speed, sediment sound speed, incident angle, sensors height, and seabed sediment thickness.

Note that the sound speed of the deposited layer tends to become faster as deeper, but it is regarded as approximately constant and not requiring strictness in this compensation.

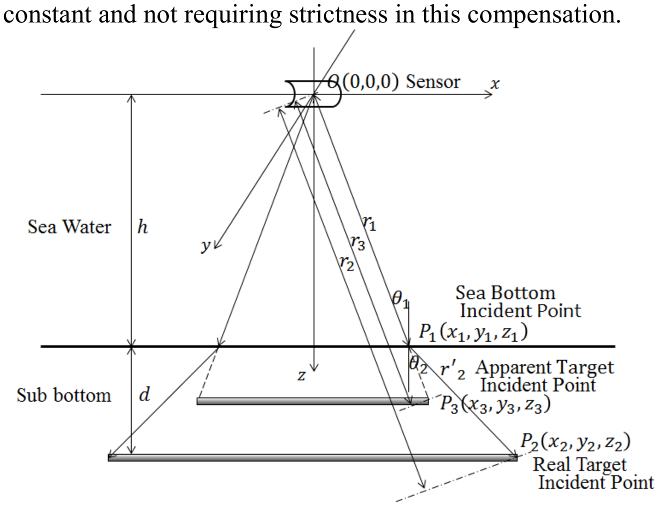


Fig.4 Real target and apparent target by refraction

In Fig.4, $O(0,0,0)$ is coordinate position of SBSAS, and the x-axis is in the azimuth direction, the y-axis is in the distance direction, and the z-axis is in the depth direction. Sensor is moved at a constant speed v on the x-axis.

Here,

h: Altitude of the sensor from the seabed

d: Thickness of the deposited layer

r_1: Slant distance between the seabed and the sensor

θ_1: Incident angle between the z axis and r_1

r_2: Slant distance between the targets in the deposited layer and the seabed

θ_2: Refraction angle between the z axis and r_2

Then,

$$r_1 = h/cos\theta_1 \tag{1}$$

$$r_2 = \sqrt{(h \cdot tan\theta_1 + d \cdot tan\theta_2)^2 + (h+d)^2} \tag{2}$$

$$r'_2 = d/cos\theta_2 \tag{3}$$

$$r_3 = r_1 + n_{21} \cdot r'_2 \tag{4}$$

Here, n_{21} is the refractive index, c_1 the speed of sound in seawater, and c_2 the speed of sound in deposited layer, by the Snell's low,

$$n_{21} = \frac{sin\theta_1}{sin\theta_2} = \frac{c_1}{c_2} \tag{5}$$

From the ratio of the slant distance r_3 and r_2, sound speed compensation factor α is, by (1) (2) (3) (4) (5),

$$\alpha = \frac{r_3}{r_2} = \left(\frac{h}{cos\theta_1} + n_{21} \cdot \frac{d}{cos\theta_2}\right) \cdot \{(h \cdot tan\theta_1 + d \cdot tan\theta_2)^2 + (h+d)^2\}^{-0.5} \tag{6}$$

According to (5)(6), α only dependents on the incident angle θ_1, sensor height h, and the deposited layer thickness d.

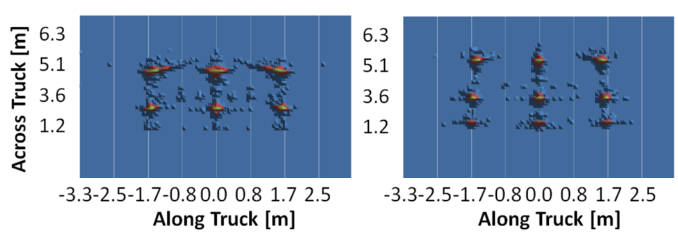
Meanwhile, in [1], the acoustic signal $pp(\tau, t; r)$ is a function of slant distance $R(t; r)$ between the target and sensor [1].

$$pp(\tau, t: r) = a(t, r)s_0\left(\tau - \frac{2}{c} \cdot R(t: r)\right) \cdot \exp\left\{-j\frac{4\pi}{\lambda} \cdot R(t: r)\right\} \tag{7}$$

Now, the apparent distance $R(t; r)$ is obtained by multiplying the sound velocity correction factor α to the real distance $R'(t; r)$.

$$R(t: r) = \alpha \cdot R'(t: r) \tag{8}$$

Simulation results of sound speed compensation before and after are shown in Fig. 5 under the following condition, $h = 6m, d = 1m, c_1 = 1500\,m/s, c_2 = 2000\,m/s$.



Before compensation After compensation

Fig.5 Sound speed compensation with 9 targets

9 targets are separated by sound speed compensation.

B. Ships velocity compensation

Between the pulse repetition frequency PRF and maximum target distance R_{max}, we must satisfy the following condition.

$$PRF < \frac{C}{2R_{max}} \tag{9}$$

Given the intended use, R_{max} of SBSAS is believed to be about 50m, and PRF in this case is about 15Hz from (9).

As shown in (10), synthetic aperture processing is adjusted to keep constant the moving distance between transmissions to match the ship velocity v, PRF and azimuth sampling frequency fas.

$$PRF = \frac{fas}{E} = \frac{2 \cdot v}{d \cdot E} \tag{10}$$

d: Spacing of receivers
E: Number of receivers

For example, when $v = 0.5\,m/s$, of $E = 5$, $d = 10cm$, PRF is 2Hz, and it can be lower than 15Hz.

However, the small boat equipped with SBSAS is influenced with wind and tide, and ship velocity is varied frequently. Therefore, it is difficult technically to change the PRF any time so as to satisfy (10).

So during the recording time of SBSAS, we have chosen fas_0 and PRF_0 to set provisional speed v_0 to satisfy (10).

$$PRF_0 = \frac{fas_0}{E} = E \cdot PRF = \frac{2 \cdot v_0}{d} \tag{11}$$

To be the conditions described from (11), $PRF_0 = E \cdot PRF$ is 10Hz, and $fas_0 = E \cdot fas$ is 50Hz.

When the synthetic aperture processing is done, by performing with original PRF and original fas, velocity compensation is accomplished.

It should be noted that, simultaneously recording and reproducing the acoustic signal, it is possible to perform online processing equivalently.

We have developed two velocity compensation methods.

(a) Velocity compensation method by delay correction (method1)

If the velocity v does not meet $fas/v = 2/d$ that satisfy (10), we perform delay correction described below, which we call velocity compensation method1.

Fig.6. is illustrating the principle of velocity compensation method1 by delay correction.

Left of Fig.6 shows a transmitter T● to transmit at a pulse repetition frequency PRF_0, receivers R0-R4○ to receive at a azimuth sampling frequency fas_0, and DPCA (Displaced Phase Center Antenna)[4] of which is in the intermediate position of the receivers and transmitter, and indicates these locations of each ping.

If $v = v_0$, the difference in the first position of DPCA5 and the last position of DPCA0 is equal to the receiver spacing d, the synthetic aperture processing is performed correctly, but when $v \neq v_0$, the difference in the first position of DPCA5 is wider than the receiver spacing d, then the degradation occurs to azimuth directional characteristics.

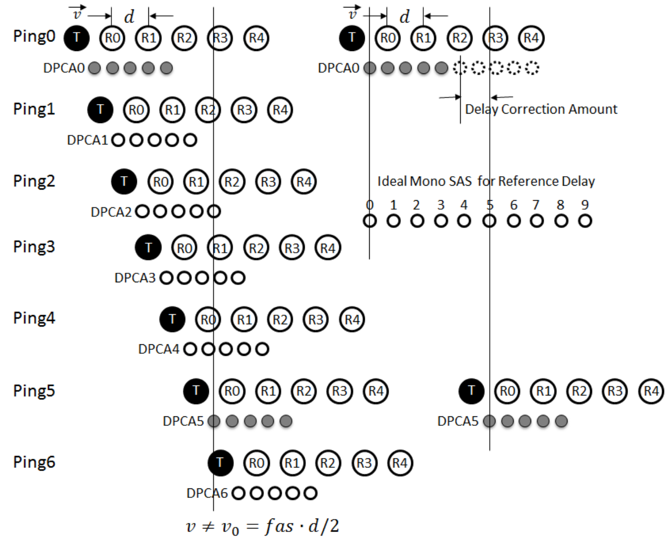


Fig.6 Velocity compensation method1 by delay correction

Therefore, in the right diagram of Fig.6, in parallel with SBSAS moving at velocity v, it is assumed that the virtual single channel SAS is moved at a speed v in synchronization with the PRF to satisfy (10). If, v will be varied from (10), by the difference in distance between the position of the virtual SAS and the position of the SBSAS, we correct the delay difference of the acoustic signal, to suppress the errors of the synthetic aperture processing.

For example, as a result of simulations of $E = 5$, $d = 10cm$, $v_0 = 0.5m/s$, $fas = 10Hz$, when $v = 1.2v_0$, the side lobe level is -18dB without delay correction, and , -28dB or less with correction. (Fig.7)

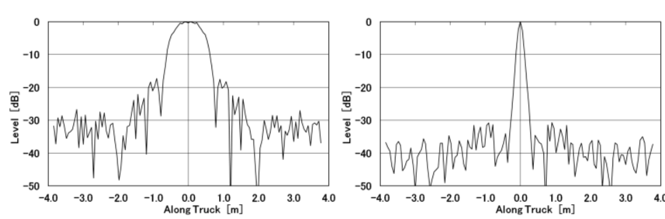


Fig.7 Azimuth characteristic by delay correction

From this result, it can be seen that the beam width in the azimuth directivity is improved significantly by performing the delay correction and azimuth resolution of original has been recovered.

In order to know the limitations of the velocity compensation, simulation was performed shown in fig.8, under the following conditions, $E = 5, d = 10cm, v_0 = 0.5m/s, fas = 10Hz$. When velocity v is changed from v_0 to $5v_0$, the simulation results of the delay correction are as follows.

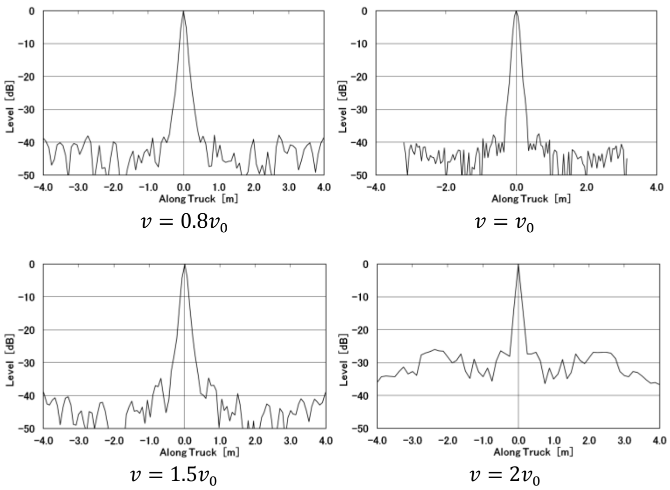


Fig.8 Azimuth characteristic by delay correction

From this result, when the velocity is $v \leq 2v_0$, side lobe level is -25dB or less, and velocity compensation of the current method is effective.

(b) Velocity compensation method by ping interval re-sampling (Method2)

In order to cope with wider velocity change, we propose a ping distance sampling method described below, which we call velocity compensation method2.

During the reproducing acoustic signals, PRF is used by re-sampling the p ping interval of the acoustic signals,

$$fas = \frac{2 \cdot v}{d} \cong \frac{E}{p} \cdot PER \quad (1 \leq p \leq E) \qquad (12)$$

Reproduced signal by choosing p is the closest v that satisfies (10).

Fig.9. is an illustration of the principle of velocity compensation method2 by ping interval re-sampling. Left diaphragm of Fig.9 is the case of $v = v_0$, the difference in the first position of the DPCA5 and the last position of DPCA0 is equal to the receiver interval d.

Right diaphragm of Fig.9 is the case of $E = 5, p = 4$, that is $v = 5/4\, v_0$ in (12). The difference in the first position of the DPCA4 and the last position of DPCA0 is equal to the receiver spacing d.

In a similar manner, by properly selecting ping interval p, we can chose optimal v.

That is,

$$v = 5/p \cdot v_0 \quad (1 \leq p \leq 5) \qquad (13)$$

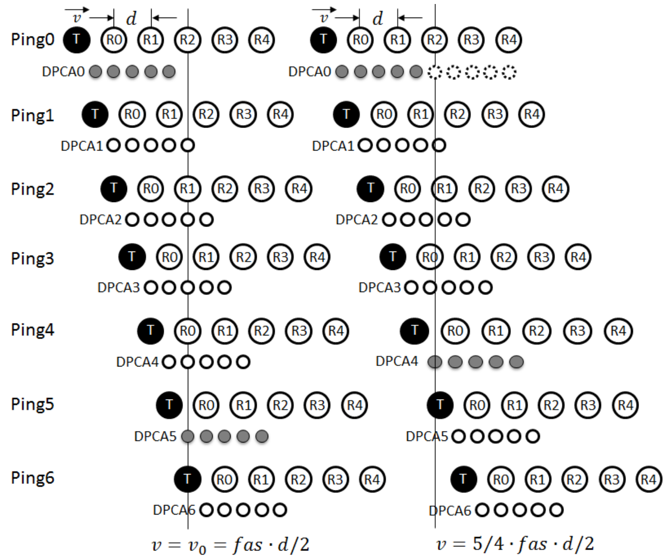


Fig.9 Velocity compensation method2 by ping interval re-sampling

In the case where p is changed from 5 ping interval to 1, $PRF_0 = 50Hz, E = 5, d = 10cm, v_0 = 0.5m/s$, simulation results are shown in Fig.10.

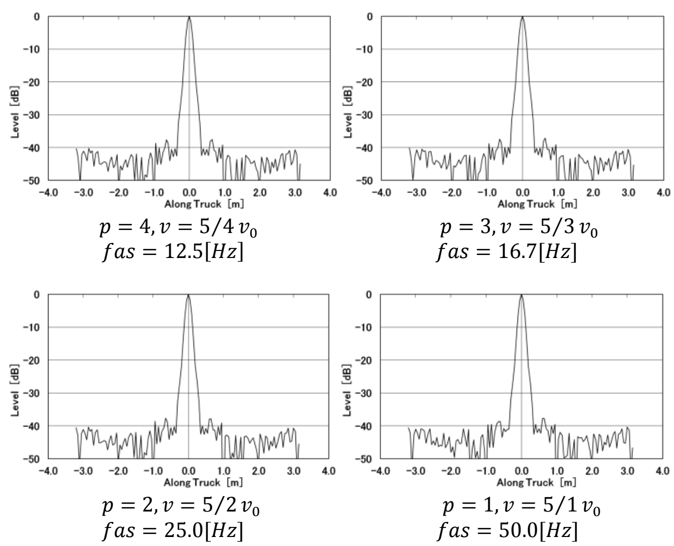


Fig.10 Azimuth characteristic by ping interval re-sampling

From this result, in the case of $v = E / p \cdot v_0$, side lobe level is below -38dB, and the speed compensation by this method is sufficient.

We combine method1 and method2 that have been described up to now, while suppressing the error of the azimuth characteristic, a wide range of velocity correction is possible from $v = v_0$ to $v = 5v_0$.

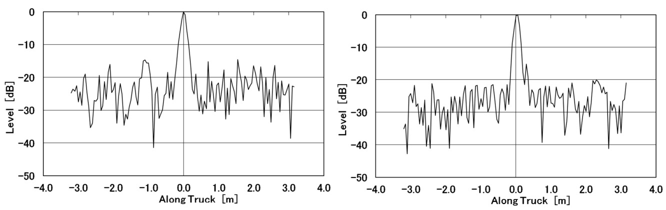
C. Visibility Improvement

Increasing the distance resolution is effective to improve the visibility. However, the SBSAS movement is intense for mounting on small boats, and there is a limit to the motion compensation. Therefore, we adapt to obtaining as many as possible the echoes from the target, and intend to improve visibility.

As shown in Fig.9, p pieces different receivers receive same target echoes in the same position, at different time.

The phases of target signals can be expected the same, but those of the background noise are different. Therefore, by vector adding the received signals, background noises are suppressed, and visibility is improved as a result.

In Fig.11, we show the simulation results of the visibility improvement by vector adding processing, under the condition, $S/R = -10dB, p = 5$, and the azimuth directivity before and after processing are shown.



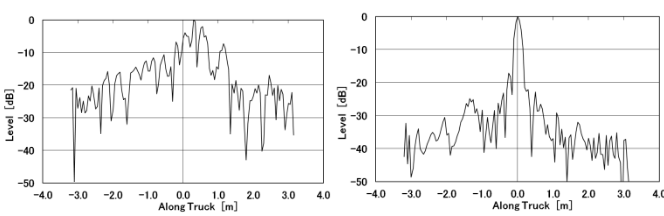
Before After

Fig.11 visibility improvement by vector adding

D. Motion Compensation

By calculating the distance between the virtual SAS and SBSAS which reflects the detected motion amount from the reference target position, and feeds back the delay amount to the received signal, and performs motion compensation.

Fig.12 is the simulation result of the azimuth directional when adding 3-axis sinusoidal motions (surge, sway and heave) of the 6.4s period with $1.4m_{rms}$ amplitude each.



Before After

Fig.12 motion compensation

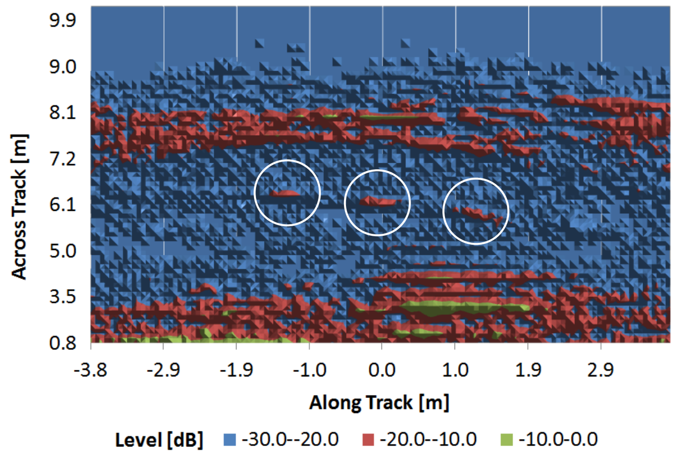
E. Offline Processing

As we has described up to now, by recording the acoustic signals in PRF_0 of E times PRF conventional, velocity v even if varied, it is possible to attempt offline compensation process in various ways.

V. Field Experiments Result

In Fig.13, the output image is shown.

We have confirmed by GPS where the targets are in this position.



$v = 0.76\,m/s, h = 4.7m, d = 4.7m, c_2 = 1800\,m/s,$
$E = 5, p = 4, fas = 12.5Hz, v/v_0 = 1.22$

Fig.13 SBSAS output image with targets

VI. Conclusions

SBSAS have been developed to be mounted on small ships, and to detect a target of the deposited layer with high resolution.

Even in circumstances robust high impact of tidal and wave, by recording at a pulse repetition frequency higher than conventional, SBSAS makes it possible to optimize various processes described in this paper.

VII. TOWARD THE FUTURE

The method in this paper is not the only and not the best way. However, by a faster pulse repetition frequency, it is possible to obtain more information of the target, and we will continue to develop better methods using this information effectively.

It is also necessary to proceed with verification in real sea level data, and we will improve the visibility of the target in the various process.

ACKNOWLEGMENT

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