High resolution side-looking sonar by synthetic processing on image planes

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1. INTRODUCTION

In the field of radar, synthetic aperture method is commonly used in order to obtain high resolution with rather short real aperture. In the field of sonar, however, synthetic aperture method is rarely used because surface wave motions can result in large deviation of a ship from the desired sonar track to be used in the synthetic aperture method.

This paper proposes a new synthetic aperture method for sonar signal processing, i.e., to correct deviation of each real aperture due to undesired ship movement and synthesize each real aperture on image plane to obtain a long synthetic aperture with high azimuthal resolution. Successive real apertures are supposed to take positions to overlap the previous one with some positional deviation from the ideal sonar tracking line. Signals from overlapping parts are used to correct the image data of non-overlapping part. Each procedure is to do on image plane obtained from received signal data by Fourier transforms. This method is within the scope of linear signal processing and is free from pseudo peaks often appear in non-linear processes such as MEM[1].

First, we introduce a received image on a real aperture which has positional errors and deviation from the sonar tracking line. By comparing this image and the ideal image, we discuss the strategy and basic formulation of this method. According to this strategy, we make our model and synthesize apertures to get high resolution image by computer simulation.

2. THE IMAGE ON THE APERTURE WITH POSITIONAL ERRORS

We assume that the receiver array, or aperture, is located in the x-z plane and the ideal sonar tracking line is x-axis. Let Q be the location of an element of the array. The azimuth (θ) is the angle from z-axis as in Fig.1 and we use $U = \sin\theta$ as an independent variable in the following analyses. Our interest is to get high azimuth resolution and this can be done best when the target is located around z axis. Then we assume that the target is located within $-M<U<M$ in the far field. The image of the target to be obtained on an infinitely long array on the x-axis, or "true image" is defined as G(U) here. When $U \ll 1$, the distance between $Q(x_i, z_i)$ and the origin in the x-z plane, q is

$$q = x_i \cdot \sin\theta + z_i \cdot \cos\theta$$

$$\fallingdotseq x_i U + z_i (1-1/2 \cdot U^2). \qquad (1)$$

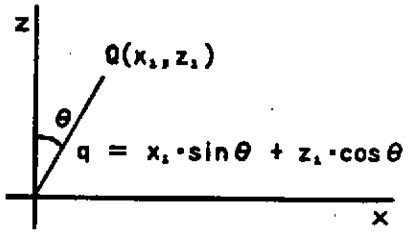

Fig.1 definition of aperture element location

Amplitude of the received signal at $Q(x_1, z_1)$ from the target is expressed as

$$f(x_1, z_1) = \int_{-M}^{M} G(U) e^{j2\pi q} \, dU$$
$$\doteqdot \int_{-M}^{M} G(U) e^{j2\pi (x_1 U + z_1 (1 - \frac{1}{2} U^2))} \, dU \qquad (2)$$

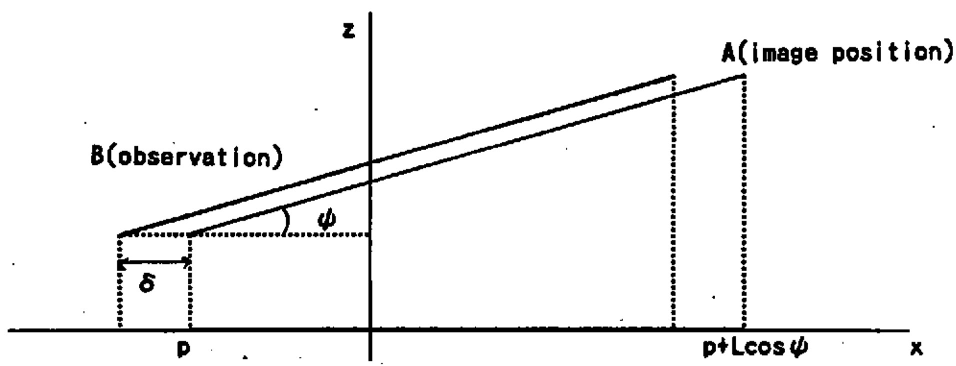

Fig.2 observation and image position

Next, We consider the image on the real aperture B which is deviated from the x axis as in Fig.2. We further assume that the image is calculated as if the aperture is located at A. Under this condition, there are three error parameters in comparison with the "ideal" aperture which is located on the x-axis, form p to p+Lcosψ. They are (i) δ : the gap in x direction or in travel distance, (ii) ζ : the gap in z or lateral location, (iii) ψ : the rotation angle from x-axis. The signal amplitude observed at each element located at (x, z) on the aperture A is easily derived from Eq.(2) as

$$f_{obs}(x) = \int_{-M}^{M} G(U) e^{j2\pi (xU + (\tan\psi \cdot x + \zeta)(1 - \frac{1}{2} U^2))} \, dU \qquad (3)$$

The image can be made from Eq.(3) by Fourier transform. However, due to the error δ in the x direction, we have to make the image from fobs(x+δ), where the range x is from p to p+Lcosψ.

$$F_{obs}(X) = \int_{p}^{p+L\cos\phi} f_{obs}(x + \zeta) e^{-j2\pi xX} \, dx$$
$$\doteqdot e^{j2\pi(\delta \tan\phi + \zeta)} \cdot L\cos\psi$$
$$\int_{-M}^{M} G(U) \mathrm{sinc}\{L\cos\psi\,(U - (x - \tan\psi + \tfrac{1}{2} U^2 \tan\psi))\} e^{j2\pi (U - (X - \tan\phi))(p + \frac{1}{2} L\cos\phi)}$$
$$e^{j2\pi \delta U} \cdot e^{j2\pi(-\frac{1}{2} U^2)(\tan\phi(\delta + p + \frac{1}{2} L\cos\phi) + \zeta)} \, dU \qquad (4)$$

Since U is much smaller than unity, we can neglect terms containing U^2.

$$F_{obs}(X) \fallingdotseq e^{j2\pi(\delta\tan\phi+\zeta)}\, L\cos\phi \int_{-M}^{M} G(U)\cdot \mathrm{sinc}\{L\cos\phi\,(U-(X-\tan\phi))\}\, e^{j2\pi(U-(X-\tan\phi))(p+\frac{1}{2}L\cos\phi)}\, e^{j2\pi\delta U}\cdot e^{j2\pi(-\frac{1}{2}U^2)(\tan\phi(\delta+p+\frac{1}{2}L\cos\phi)+\zeta)}\, dU \quad (5)$$

This is the image obtained from the signal on aperture B and contains three error parameters.

3. THE STRATEGY OF IMAGE SUBSTITUTION

The the ideal image to be obtained in the x-axis aperture from p to p+L$\cos\phi$ is

$$F(X) = L\cos\phi\cdot\int_{-M}^{M} G(U)\cdot \mathrm{sinc}\{L\cos\phi\,(U-X)\}\, e^{j2\pi(U-X)(p+\frac{1}{2}L\cos\phi)}\, dU \quad (6)$$

Our strategy is to make Eq.(5) as close as possible to Eq.(6) by controlling δ, ϕ, and ζ. By comparing Eq.(5) with Eq.(6), we obtain the following information.

(i) The first term in Eq.(5)

$$e^{j2\pi(\delta\tan\phi+\zeta)} \quad (7)$$

does not apear in Eq.(6). It is caused due to the aperture deviation from the x-axis and all three error parameters must be known for the correction.

(ii) The convolution's core part in Eq.(5) is

$U-(X-\tan\phi)$. (8)

This means that image position is shifted by $\tan\phi$.

(iii) G(U) is multiplied by two terms which depending on U and U^2.

$$e^{j2\pi\delta U} \quad (9)$$

$$e^{j2\pi(-\frac{1}{2}U^2)(\tan\phi(\delta+p+\frac{1}{2}L\cos\phi)+\zeta)} \quad (10)$$

Among the error parameters, δ and ϕ can be measured with accelerometers and gyrocompasses respectively and can be controlled. However, it is difficult to measure and control ζ for practical use. If we obtain these parameters, we can correct Fobs(X) by multipling $-\exp(j2\pi(\delta\tan\phi+\zeta))$ and we can correct the image position in Eq.(8). As to Eq.(9), we consider the method to controll δ to be zero. Eq.(10) contains U^2 and can be considered unity due to our assumption $U^2 \fallingdotseq 0$. But when the synthetic aperture length become longer and longer, $p\cdot\tan\phi$ may become harmful. Therefore, we have to controll $\phi \fallingdotseq 0$ by mechanical devices.

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According to above discussion, the strategy is following:

(1) To get $\psi \fallingdotseq 0$, we stabilize the aperture direction by the mechanical feedback system including the gyrocompass, etc.

(2) If δ is very small, we do nothing. Accuracy of δ depends on how we measure the aperture position correctly, and we need a high accuracy accelerator.

(3) On the contrary to ψ or δ, it is difficult to obtain proper devices to measure ζ accurately. Next, we discuss how to find ζ by utilizing information from overlapping part of the apertures in the following chapter.

4. SYNTHETIC APERTURE METHOD USING TWO IMAGE PLANES

Suppose there are two apertures on x-z plane and they are controlled to be $\psi=0$ and $\delta=0$ according to above strategy (Fig.3). These have same length L and one is located p=0, the other p=a, where $0 < a < L$. Under this condision, we consider to synthesize these apertures and obtain L+a length aperture image. We obtain two images Fobs1(X) and Fobs2(X) from these apertures.

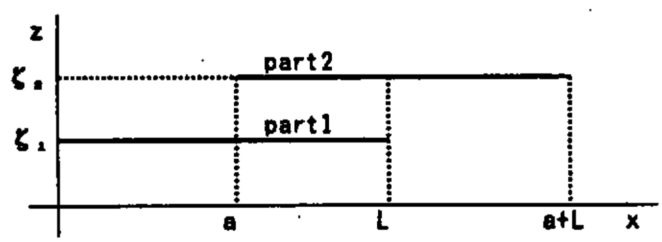

Fig.3 aperture position

$$F_{obs1}(X) = e^{j2\pi\zeta_1} L\int_{-M}^{M} G(U) e^{j2\pi(U-X)(\frac{1}{2}L)} \operatorname{sinc}(L(U-X)) e^{j2\pi(-\frac{1}{2}U^2)\zeta_1} dU$$

$$\fallingdotseq e^{j2\pi\zeta_1} \widetilde{F}(X)|_{p=0,\, len=L} \qquad (11a)$$

$$F_{obs2}(X) = e^{j2\pi\zeta_2} L\int_{-M}^{M} G(U) e^{j2\pi(U-X)(\frac{1}{2}L)} \, \mathrm{sinc}\{L(U-X)\} e^{j2\pi(-\frac{1}{2}U^2)\zeta_2} \, dU$$
$$\fallingdotseq e^{j2\pi\zeta_2} \tilde{F}(X)|_{p=a,\, len=L} \tag{11b}$$

where $$F(X)|_{p=a,\, len=L} = L\int_{-M}^{M} G(U)\cdot \mathrm{sinc}\{L(U-X)\} e^{j2\pi(U-X)(a+\frac{1}{2}L)} dU \tag{12}$$

Also we obtain two image data from each overlapping part:

$$F_{part1}(X) = e^{j2\pi\zeta_1}(L-a)\int_{-M}^{M} G(U) e^{j2\pi(U-X)(\frac{1}{2}(L-a))}$$
$$\mathrm{sinc}\{(L-a)(U-X)\} e^{j2\pi(-\frac{1}{2}U^2)\zeta_1} \, dU$$
$$\fallingdotseq e^{j2\pi\zeta_1}\cdot\tilde{F}(X)|_{p=a,\, len=L-a} \tag{13a}$$

$$F_{part2}(X) = e^{j2\pi\zeta_2}(L-a)\int_{-M}^{M} G(U) e^{j2\pi(U-X)(\frac{1}{2}(L-a))}$$
$$\mathrm{sinc}\{(L-a)(U-X)\} e^{j2\pi(-\frac{1}{2}U^2)\zeta_2} \, dU$$
$$\fallingdotseq e^{j2\pi\zeta_2}\cdot\tilde{F}(X)|_{p=a,\, len=L-a} \tag{13b}$$

Using these equations, we compute synthetic aperture image.

$$F_{obs1}(X) + e^{j2\pi(\zeta_1-\zeta_2)}\cdot F_{obs2}(X) - \frac{1}{2}\{F_{part1}(X) + e^{j2\pi(\zeta_1-\zeta_2)} F_{part2}(X)\}$$
$$= e^{j2\pi\zeta_1}\cdot\tilde{F}(X)|_{p=0,\, len=L+a} \tag{14}$$

In Eq.(14) $\exp(j2\pi(\zeta_2-\zeta_1))$ is computed by the phase comparison between Fpart1(X) and Fpart2(X). It is important that this can be computed using information from recieved signal itself, and not from other measurement devices.
That is

$$e^{j2\pi(\zeta_1-\zeta_2)} = \frac{\int\phi(X)\arg(\phi(X))dX}{\int\phi(X)dX} \tag{15}$$

where $\phi(X) = F_{part1}(X) \cdot F^{*}_{part2}(X)$

By this method, we can obtain long synthetic aperture of length L+a. It is then possible to construct much longer synthetic aperture by repeating this synthesis procedures.

5. SIMULATION RESULTS

We confirm our theory by computer simulations. The aperture length is 10 wave length and element interval is 0.5 wave length. The signal pattern (G(U)) has two separate peaks as shown in Fig.4 and the real aperture moves like in Fig.5, where the number is receiving count. Under this conditions, we simulate two kinds of situations.

First, we simulate the model when only signals are arriving. Fig.6 shows the image obtained from single real aperture that can't separete two peaks at all. On the other hand, as in Fig.7, image obtained from the synthesized aperture shows separation of two peaks clearly.

Next we consider the case when the signal contains the noise spatially white, has zero mean, and is independent of the signals, with S/N=3dB. The synthetic aperture image as shown in Fig.8 still shows peak separation.

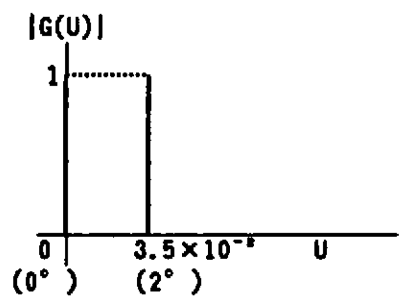

Fig.4 signal pattern

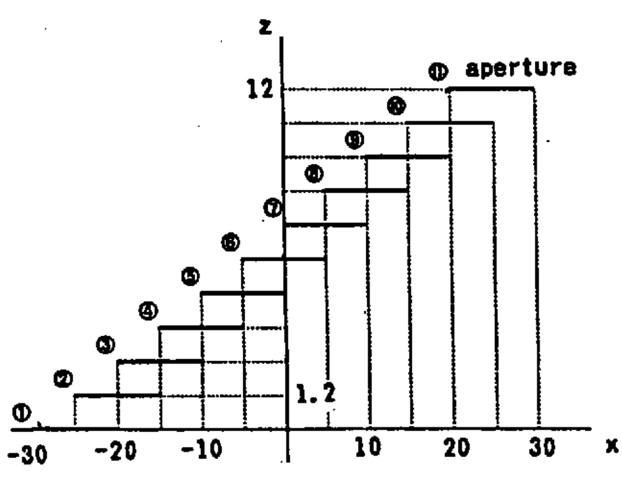

Fig.5 aperture movement

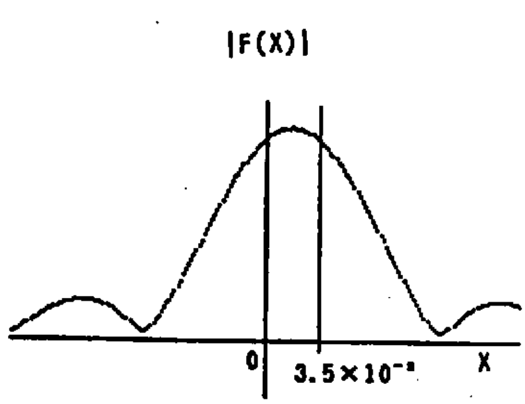

Fig.6 real aperture image

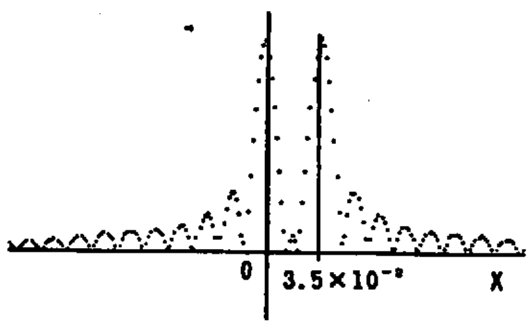

Fig.7 synthetic aperture image
(signal only)

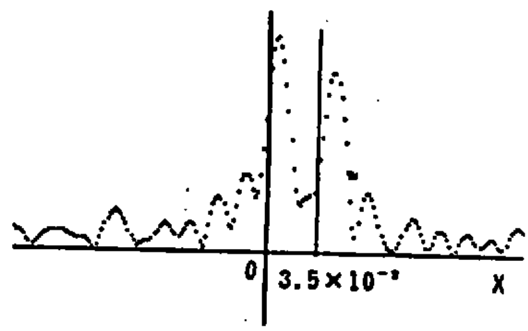

Fig.8 synthetic aperture image
(S/N=3dB)

6. SUMMARY

In this paper, we propose the synthetic aperture method with array position error correction that synthesizes on the image plane. Errors are in travel distance and lateral locations and array direction. Distance location and array direction errors can be measured and controlled by mechanical devices readily available in regular ships. Error in parallel movement can be measured and corrected from the signals of overlapping part of real apertures. We confirmed the validity of this method by computer simulation.

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7. REFERENCES

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