A NEW METHOD OF IMPROVING THE AZIMUTH RESOLUTION IN THE FORWARD-LOOKING SONAR BY DOPPLER BEAM SHARPENING TECHNIQUE

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Abstract: *Doppler beam sharpening(DBS) is a technique to improve radar azimuth resolution. This paper introduces the technology field of sonar, to promote forward-looking sonar azimuth resolution. 1, The DBS signal model is established, and the relationship between the theoretical azimuth resolution and the wavelength, the length of the array, the azimuth angle and the range is analyzed. 2，The incompatibility of the DBS technology in forward-looking sonar is compared with the DBS technology in radar , and the beam dwell time is improved by the method constrained beam width.3,To ensure the signal coherent superposition in one unit of range resolution unit, the range migration correction with the variable range is used.4，The correspondence between the frequency and the angle is established, to calibrate the coordinate position of the target. Finally, the simulation results show that the DBS technique can effectively improve the azimuth resolution of the forward-looking sonar..*

Keywords: *DBS, forward-looking sonar, azimuth resolution*

1. INTRODUCTION

Two-dimensional sonar imaging technology is divided into two categories: real aperture imaging (RAI) and synthetic aperture imaging (SAI). Real aperture imaging sonar mainly consists of side scan sonar and forward-looking sonar. Side-scan sonar equipment is simple, cost-effective, widely used in marine mapping. However, side-scan sonar mode operation using positive side, there is a side-looking mode operation fatal drawback: the presence of dead zones below the platform. The principle of synthetic aperture sonar is different from the real aperture sonar, but its work mode is also used in positive side view mode work, therefore the bottom of the platform inevitably there is a blind spot. In order to overcome the problem of the existence of a blind spot in the side-scan sonar and the synthetic aperture sonar, it is common to use forward-looking sonar as blinded sonar.

The forward-looking sonar belongs to real aperture imaging sonar, whose azimuth resolution is limited by the wavelength, aperture ratio and distance, such that beam width of SEABAT7128 is 0.5 degrees, and the azimuth resolution has been as low as 1.25m at a distance of 150 meters. The resolution of forward-looking sonar is seriously mismatched with the resolution of synthetic aperture sonar, and the resolution of the international mainstream synthetic aperture sonar has reached 3cm. The only effective way to improve the resolution of classical array is to increase the ratio of aperture to wavelength, at the cost of increasing the number of channels, the size of the array and the complexity of the equipment.

Technique of Doppler Beam Sharpening (DBS) [1-6] for enhancing radar azimuth resolution divides the echoes in the same beam into a set of "Doppler beams" by Doppler analysis, and the ratio of the original beam width to the Doppler beam width is called the "sharpen ratio". A new generation of airborne pulse Doppler radar with DBS can provide a clearer radar map of the local ground in the long distance ahead of time, with a sharpening ratio of 32-64.

This paper introduces the idea of radar DBS technology into forward-looking sonar to improve the azimuth resolution of forward-looking sonar.

2. SIGNAL MODEL OF THE FORWARD LOOKING SONAR

SAR imaging algorithm is used to solve the problem of imaging algorithm of the forward-looking radar. However, unlike forward-looking radar, the forward-looking sonar does not satisfy the assumption of non-stop-go-stop so it can’t copy the SAR imaging algorithm. First, it is necessary to establish the accurate delay history under the condition of non-stop-go-stop of the forward-looking sonar. The geometry of forward looking sonar is shown in figure 1.

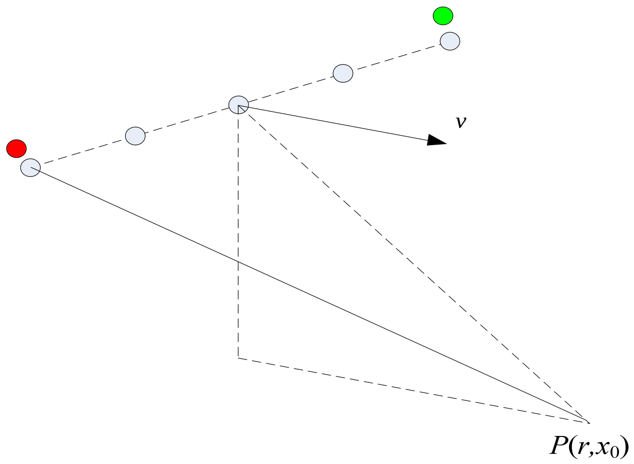

Fig.1: The geometry of forward-looking sonar.

Ignore the position of the transmitting and receiving array in the height direction, the horizontal coordinate zero at the receiving array axis of symmetry. Assuming that the number of elements is even, the position of the left transmitting element is $x_{TL} = -N \cdot d / 2$, the position of the i th receiving element is $x_i = -(N/2 - i)d - d/2$, the sonar is uniform motion in a straight line, t_{i,L^*} is the accurate delay of the i th receiving element, the position of the target is $P(r, x_0)$,and x_0 is 0, the accurate delay history can be obtained by :

$$R_{TL} + R_i(r) = ct_{i,L^*} \tag{1}$$

Substituting $R_{TL} = \sqrt{x_{TL}^2 + r^2}$ and $R_i(r) = \sqrt{x_i^2 + (r - vt_{i,L^*})^2}$ into (1)， t_{i,L^*} is given by

$$t_{i,L^*} = \frac{B + \sqrt{B^2 - AC}}{A} \tag{2}$$

where $A = (c^2 - v^2)$， $B = \left(c\sqrt{(x_{TL}^2 + r^2)} - r \cdot v\right)$， $C = (x_{TL}^2 - x_i^2)$

3. THE METHOD OF REALIZING DBS IN THE FORWARD LOOKING SONAR

The working geometry of the forward looking sonar is shown in figure 2. At the 0 moment, the azimuthal angle, looking down angle and cone angle are α, β, ψ , respectively. The position of the target P is $(r, 0)$.

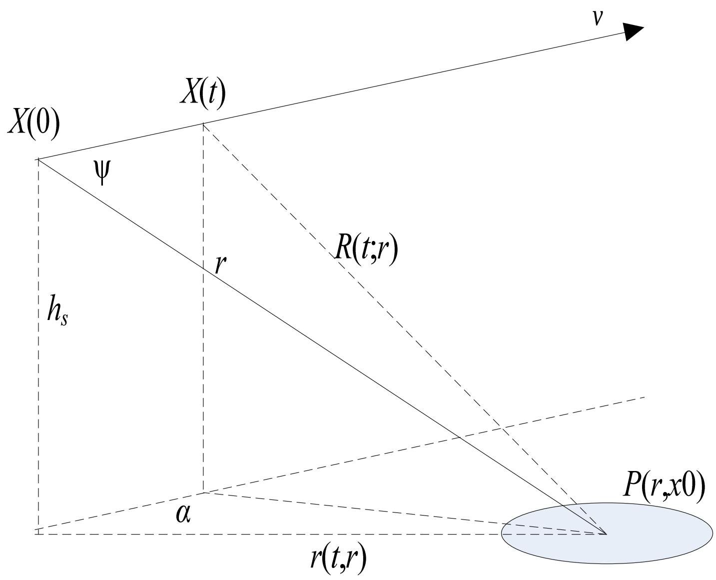

Fig.2: The working geometry of the forward looking sonar

When the location of sonar is $X(t) = vt$, the instantaneous slant range $R(t;r)$ 为 can be written by

$$R(t;r) = \sqrt{r^2 + (vt)^2 - 2r(vt)\cos\psi} \approx r - (vt)\cos\psi + \frac{(vt)^2}{2r}\sin^2\psi \tag{3}$$

According to (3), Doppler phase history is given by

$$\phi(t;r) = -\frac{4\pi R(t;r)}{\lambda} \approx -\frac{4\pi}{\lambda}\left[r - (vt)\cos\psi + \frac{(vt)^2}{2r}\sin^2\psi\right] \tag{4}$$

According to (4), Doppler frequency can be obtained by

$$f_d(t;r) = \frac{1}{2\pi}\frac{d}{dt}\phi(t;r) \approx \frac{2v}{\lambda}\left[\cos\psi - \frac{(vt)}{r}\sin^2\psi\right] = \frac{2v\cos\psi}{\lambda} - \frac{2v}{\lambda}\frac{(vt)}{r}\sin^2\psi = f_{d0} + f_{d,l} \tag{5}$$

Equation (5) shows that equation (3) can be written in terms of time-independent term and the term that is linearly related to time. The biggest difference with synthetic aperture sonar is that DBS only uses difference of Doppler frequency to distinguish targets, which is belong to non-focus synthetic aperture imaging, so the resolution is inferior to focused synthetic aperture imaging. But the signal processing of the synthetic aperture imaging is complexity and the signal processing of DBS technical is simple.

The relation between Doppler frequency and azimuthal and pitching angle in terms of (5) can be written by

$$f_{d0} = \frac{2V}{\lambda}\cos\alpha\cos\beta \tag{6}$$

Assuming that there are two scattering points in the same beam when β is constant, and the difference of Doppler frequency is caused by the difference of azimuthal angle, the difference of Doppler frequency can be formulated as follows:

$$\Delta f_{d0} = -\frac{2V}{\lambda}\sin\alpha\cos\beta\cdot\Delta\alpha \tag{7}$$

Then the azimuthal resolution can be written by

$$\rho_\alpha = -\frac{\lambda}{2V\sin\alpha\cos\beta}\rho_f \tag{8}$$

Where ρ_f is frequency resolution, which is the reciprocal of the coherent accumulation time T ($\rho_f = 1/T$). Assuming that the number of coherent pulses and the pulse repetition interval are N , PRI respectively, then the azimuth resolution is

$$\rho_\alpha = -\frac{\lambda}{2V\sin\alpha\cos\beta}\frac{1}{N\cdot PRI} \tag{9}$$

According to (3)，the bandwidth of Doppler frequency is obtained by

$$B_d = \left| f_{d,l} \right|\Big|_0^T = \frac{2v}{\lambda}\frac{(vT)}{r}\sin^2\psi \tag{10}$$

According to the theory of signal processing, the frequency resolution should be greater than the bandwidth of Doppler frequency.

$$B_d \le \rho_f \tag{11}$$

Then

$$\frac{2v}{\lambda}\frac{(vT)}{r}\sin^2\psi \le \frac{1}{T} \tag{12}$$

The maximum coherent accumulation time can be obtained from the equation (12).

$$T_s = \sqrt{\lambda r / 2} / \left(v \sin \psi \right) \tag{13}$$

According to (13), the synthetic aperture length can be given by

$$L_s = T_s \cdot v \cdot \sin \psi = \sqrt{\lambda r / 2} \tag{14}$$

Then the azimuthal resolution in range r can be obtained by

$$\rho_{cr} = r \cdot \Delta \mathrm{A}_s = r \cdot \frac{\lambda}{2 L_s} = \sqrt{\lambda r / 2} \tag{15}$$

4. THE CHARACTERISTICS OF DBS IN THE FORWARD LOOKING SONAR

Compared with radar, forward-looking sonar has the following differences in DBS implementation:

a. The difference in scanning mode

Radar usually adopts mechanical scanning, that the beam width is fixed and it is sequential scanning, so the signal processing is more complicated when dealing with DBS. The forward-looking sonar uses multi-beam mode that the beam is simultaneous. The forward-looking sonar has the narrow central beam which is the high resolution, and has the width edge beam which is the low resolution. This feature is the advantage of the forwarding-looking sonar in DBS technology DBS.

b. The range migration correction

Range migration correction for radar is not necessarily necessary[7], but forward-looking sonar has to do range migration correction because of large variability and high range resolution.

$$v \cos \alpha \cos \beta \cdot T_s \leq \frac{C}{2B} \tag{16}$$

c. Pulse repetition frequency is low

The pulse repetition frequency (PRF) of radar is very high and the number of pulses involved in coherent accumulation is large, but the PRF of forward-looking sonar is very low, which brings two problems: First, the Doppler frequency is highly ambiguous. Second, the number of pulses involved in coherent accumulation is very low.

5. SIMULATION RESULTS

To verify the validity of the DBS algorithm in the paper, simulations are carried out in this section. The system parameters are listed in Table I.

Carrier frequency	200kHz	Antenna length	0.375m
Bandwidth	50kHz	Beam direction angle	15^0
Pulse width	0.5ms	Target A coordinate	$(200m,14.5^0)$
PRI	400ms	Target B coordinate	$(200m,15^0)$
Velocity	1m/s	Target C coordinate	$(200m,15.5^0)$

Table 1: Simulation Parameters.

Fig. 3 shows the result of processing three simulated point target for different azimuthal angles. The results verify the validity of the DBS algorithm in the forward-looking sonar.

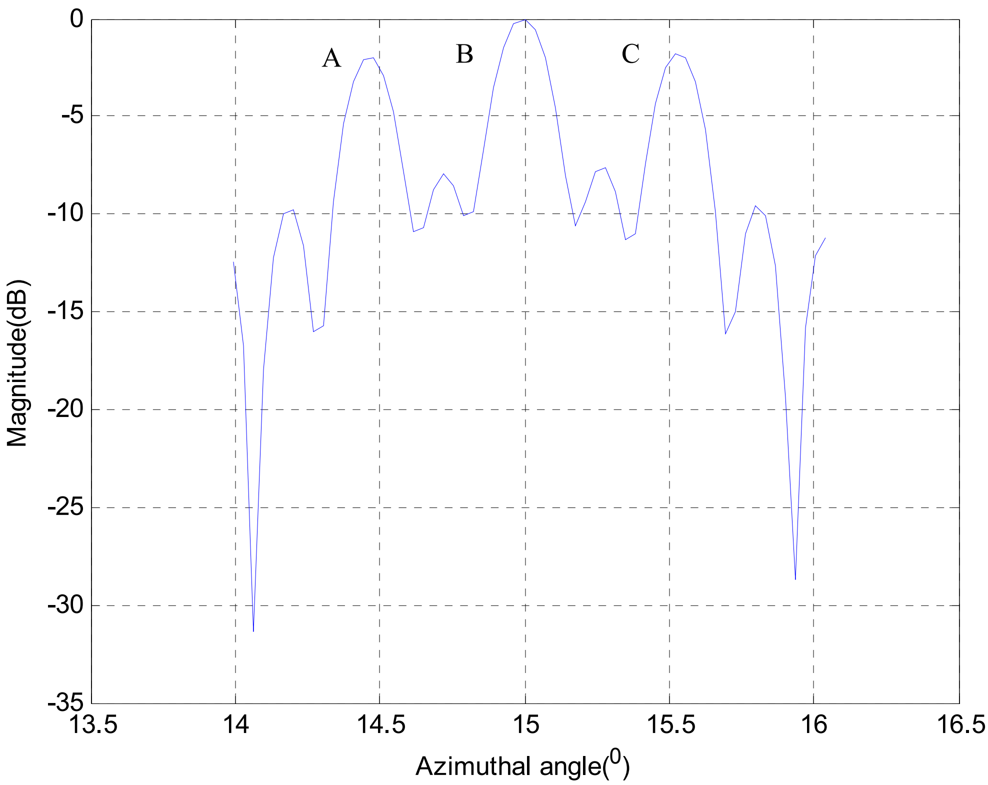

Fig. 3. Simulated the forward-looking sonar data processed using DBS.

6. CONCLUSION

This paper introduces the idea of radar DBS technology into forward-looking sonar to improve the azimuth resolution of forward-looking sonar. First, the "non-stop-go-stop" signal model of the forward-looking sonar is established. Then the DBS algorithm is applied into the forward-looking sonar and the characteristics of DBS algorithm in the forward-looking sonar. Finally, the simulations verify the validity of the DBS algorithm in the forward-looking sonar.

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