A seabed detection technology based on multi-split beam phase difference

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Abstract. In view of the difficult problem of high-precision bottom detection in multi-beam shallow sea topographic survey, a multi-beam seabed detection technology based on multi-split beam phase difference is proposed in this paper, and the realization method of this detection technology under U-shaped acoustic array is emphatically discussed. The simulation and actual measurement results show that the technology is not only capable of detecting the seabed in both mirrored and non-mirrored regions, but also can improve the detection performance of the system due to the introduction of multi-split beam, phase slope error curve and image transformation.

1 INTRODUCTION

The multi-beam topographic survey system is an efficient and fast estimation system for the time of arrival (TOA) and direction of arrival (DOA) of the echo signals in each transmitting/receiving cross beam [1]. It can accurately and rapidly map the seafloor topography within a certain width along the route, and has been widely used in ocean, river and lake geomorphology survey.

In the more than 40 years of development of multi-beam sounding technology, wide coverage and high precision sounding performance have always been the focus and difficulty of multi-beam sounding technology [2]. As the backscatter signals from different directions have the same frequency, the echo propagation loss increases with the gradual gradient of the graze, the intensity of the received echo signal weakens, and the beam broadens obviously. Therefore, for the estimation of edge beam, the base detection method based on amplitude cannot be used, but the detection method based on phase, such as the phase difference method based on split aperture, should be used.

However, for the edge beam corresponding to large grazing Angle, the signal to noise ratio of the received echo signal is very low due to the long acoustic path of echo propagation and the large back scattering loss. At this time, it is very difficult to accurately locate the zero crossing of the phase difference curve by using the conventional split aperture phase difference method only by using the single curve fitting [3].

For this reason, this paper proposes a multi beam seabed detection technology based on multi split phase difference, and discusses the principle of this technology combined with U-shaped array structure. By using a variety of split beam subarray division methods, multiple measurements of DOA phase difference curve are formed. At the same time, the least square processing is introduced to estimate the parameter error, which solves the difficult problem of designing the automatic tracking gate with the traditional phase difference detection method. The simulation and actual measurement results verify that this method still has high detection accuracy when it is used to detect the bottom of edge beam with low signal-to-noise ratio.

2 SEABED DETECTION TECHNOLOGY BASED ON MULTI-SPLIT BEAM PHASE DIFFERENCE

2.1 Phase difference function

For a U-shaped matrix structure (as shown in Fig. 1), due to its special spatial structure, when the pre-beamforming angle θ, A is the tangent point between the pre-beamforming beam and the array, the effective aperture B of the array is the distance from the tangent AE. With the change of angle θ, the effective aperture of the array changes constantly and the corresponding beam width also changes constantly. In the phase-based detection technology, in order to obtain the phase difference sequence of the beam, the array is usually divided into two sub-arrays, and the phase of the conjugate sequence of the beamforming output of the two sub-arrays is obtained. The time corresponding to the zero crossing of each phase difference sequence is the arrival time of the beam control direction echo. In order to facilitate the determination of zero, in literature [4], we emphatically discuss the principles and methods of

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sub-array allocation, including effective aperture and degree of overlap, etc.

For mult-split beam phase difference detection technology is put forward in this paper, first of all, the one contained in the direction of the beam arrays of all, on the basis of the principle of "according to delimit effective aperture array", using several different arrays of overlapping ways could be divided into two sub-array, The effective aperture of two sub-array are L_i , overlap $d_i \approx L_i / 2$ is the best [4]. Assuming that we adopt $M(M \geq 2)$ different split beam division methods, the M pairs of split beam can be obtained in a certain pre-formed direction, and then we can obtained the M phase difference sequences of the pre-formed direction beam, namely the phase difference function, can be denoted as $\Delta\varphi_i(n)$, $1 \leq i \leq M$.

As shown in figure 1, the assumption of wave front is plane, θ is the wave sound arrived angle, the i th $(1 \leq i \leq M)$ kind of split beam method, will reach the angle corresponding to the echo of effective array AB , split into a pair of overlapped sub-arrays AD and CB , then the two sub-arrays acoustics centre c_{1i} and c_{2i} respectively, the distance between them in d_i , said the phase difference between two sub-arrays can be expressed as:

$$\Delta\varphi_i(n) = 2\pi f \frac{d_i}{c} \sin \Delta\theta(n) \quad (1 \leq i \leq M) \qquad (1)$$
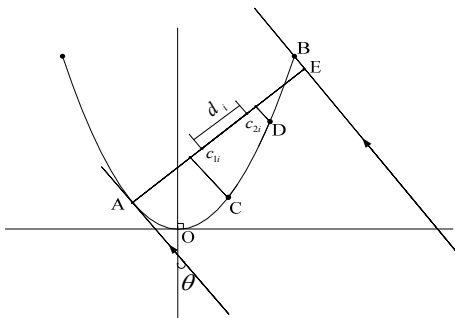

Fig. 1. Schematic diagram of split beam of U-shaped array

Equation (1) represents the phase difference estimation of the received signal at a given moment n , where, f represents the working frequency, c is the speed of sound, $\Delta\theta(n)$ represents the deviation between the arrival direction of the echo and the beam-controlled direction, and $\Delta\varphi_i(n)$ is zero when they coincide.

2.2 Phase difference error function

For the phase difference sequence obtained by different split beam division methods at the same time, it must be the seabed echo at the same azimuth. The least square estimation can be used to obtain the expression of the phase error:

$$e = \sum_{i=1}^{M} (k_i \sin \Delta\theta(n) - \Delta\varphi_i(n))^2 \qquad (2)$$

Where, k_i is the slope of the phase difference sequence $k_i = \frac{2\pi f d_i}{c}$ .Let $\frac{\partial e}{\partial(\sin \Delta\theta(n))} = 0$, get the $\Delta\theta(n)$ estimation:

$$\widehat{\Delta\theta(n)} = \sin^{-1}[\sum_{i=1}^{M} k_i \Delta\varphi_i(n) / \sum_{i=1}^{M} k_i^2] \qquad (3)$$

By substituting equation (3) into Equation (2), a value indicating the nonlinearity e of the sub-array phase difference function is obtained, which is called phase difference error function and is very small in the echo arrival time. In this method, if $M \geq 2$, the magnitude of the nonlinearity e can be calculated as long as it is below a certain threshold, so $\widehat{\Delta\theta(n)}$ can be used to estimate DOA and seabed depth. The interval determined by this threshold is called the tracking interval, and the seabed image obtained from the value of the preformed beam Angle and the arrival time function is called the phase difference error image.

2.3 Sea bottom image transformation

Phase difference in the image expressed a non-zero value within the beam from the other direction to echo, to take advantage of the non-zero value to detect underwater echo, will transform the phase difference image, said after the transformation of the image for the underwater trajectory images, it is the echo to the direction and the function of time, each pixel in image grid point value represents the likelihood of the bottom echo. For each pixel in the phase difference image, DOA is calculated by using Formula (3) and the value of pixel points corresponding to given time and DOA in the seabed image grid will increase. This indicates a high probability of seabed echo in one direction. Specific implementation steps are as follows:

First, initialize the seabed image $B(n,\alpha) = 0$, where α is DOA and n is the given moment; Calculated $\Delta\theta(n,\beta)$ by (3), add the following $B(n,\alpha)$ in the corresponding grid:

$$B(n,\alpha) \Leftarrow B(n,\alpha) + I(n,\beta) \qquad (4)$$

Where, $I(n,\beta)$ is increment, and β is pre-formed beam Angle.

$$I(n,\beta) = 1 + wA(n,\beta) \qquad (5)$$

Here, constant 1 is the phase weighting, $A(n,\beta)$ is the amplitude of the beam output at the n moment and

the pre-formed beam Angle β is the amplitude weighting, w is the global weighting factor, and is adjusted to make the amplitude weighting and phase weighting comparable. This weighting is reasonable because the seabed image represents the probability of the bottom echo in each direction of arrival, which is related not only to the phase of the echo signal, but also to the amplitude of the echo signal. In the mirror image region, the uncertainty of phase information increases, but the amplitude information is very clear, which can effectively make up for the deficiency of the traditional phase detection method, so as to realize the joint detection of amplitude and phase.

Repeat the above steps for other beams with large grazing angles to obtain corresponding seabed trajectory images $B(n,\alpha)$.

Assuming that the adoption time corresponding to the upper and lower limits of the tracking interval are n_l and n_h respectively, then the corresponding time interval $t_l = n_l \times f_s$ and $t_h = n_h \times f_s$ can be obtained by combining the sampling frequency. According to the seabed image $B(n,\alpha)$ under the corresponding beam, the amplitude weighted average of its time in the tracking interval is calculated as the estimated value of the echo arrival time (TOA) of this beam. The weighted average formula is as follows:

$$t = \sum_{i=T_l}^{T_h} A_i \cdot t_i \Big/ \sum_{i=T_l}^{T_h} A_i \qquad (6)$$

Finally, DOA-TOA estimation can be used to estimate the final seabed depth.

3 RESULTS AND ANALYSIS

The simulation assumes that both u-transmitting and receiving array is located 100 meters away from the seabed, covering an ocean depth of 8 times, the working center frequency of the system is $195kHz$, transmitting pulse width is $4ms$, and sampling frequency after baseband demodulation is $5kHz$, thus simulating and generating submarine echo receiving data of 128-channel U-array.

Under different preforming beams, the array elements of U-shaped array participating in beamforming vary. 256 pre-formed beams are formed in the range of -75 degree ~75 degree. For a certain pre-formed beam, the array elements involved in the beam formation are divided into two sub-arrays according to the principle of equal effective aperture, and the overlapping degree is changed to obtain nine different split beam modes. The seabed depth is estimated by using the above multi-split beam phase difference detection technology.

Fig.2-Fig.6 are given respectively based on multiple split beam U array processing of phase difference detection technology, Fig.2 is Phase difference sequence

under the partition mode of 9 sub-arrays with 60-degree open angle, Fig.3 is a function of phase difference error image of e, Fig.4 is underwater trajectory image, Fig.5 is multi-split beam phase difference method applied to simulate underwater detection results, Fig.6 is a traditional split aperture phase difference method applied to simulate the bottom of the sea test results.
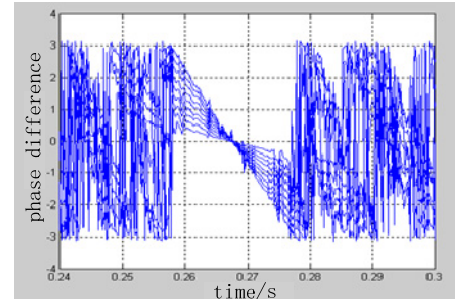

Fig. 2. Phase difference sequence under the partition mode of 9 sub-arrays with 60-degree open angle
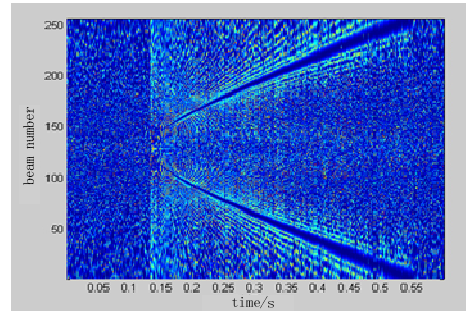

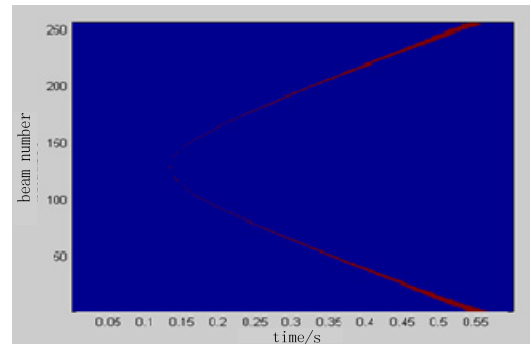**Fig. 3.** Phase difference function error image
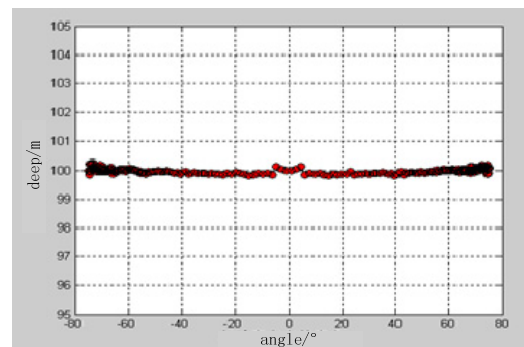

Fig. 4. Submarine trajectory image

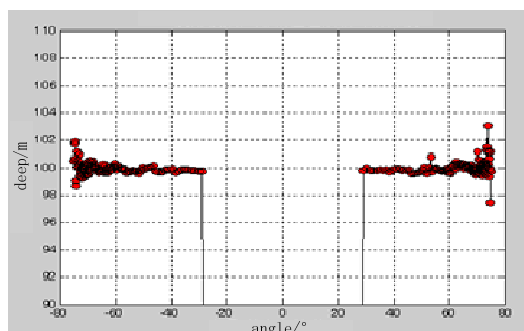**Fig. 5.** Seabed detection results by multi-split beam phase difference method

Fig. 6. Seabed detection results by traditional split aperture phase difference method
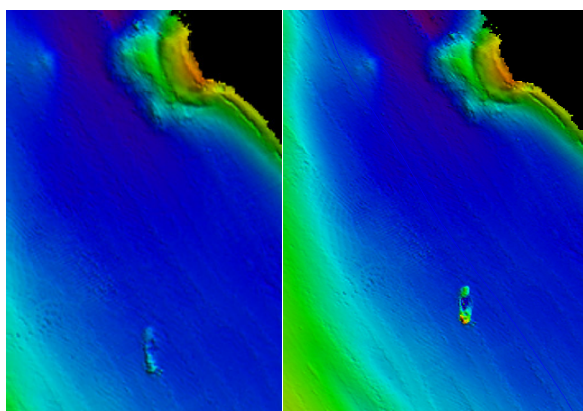

Fig. 7. Detection results by of the maritime shipwreck

Fig.7 given multi-split beam phase difference method and traditional split aperture phase difference method applied to detect the maritime shipwreck [5].

Traditional phase difference method directly to the two sub-array beamforming output phase sequence, thus proposed and looked for zero, however, we from the output of the beamforming (figure 2) as you can see, the competition with the grazing gradient is small, the spread of the echo sound growth process, the transmission loss increases, the received echo signal intensity is abate, and a significant broadening of the beam, the right of zero point estimate caused no small difficulty.

The presented multi-split beam phase difference submarine detection technology by using a variety of split beam sub-array method, divided into form on the same echo reach the direction of the phase difference measurement for many times, and combined with least-squares processing, for the calculation of phase difference instead of to the operation of the phase, simplifies the complexity of the estimated parameter error, to determine automatic tracking gate, in the low signal noise ratio of echo the edge of the beam for underwater detection, still can correctly determine trace interval, ensure the effective of continuous topography measurement. At the same time, the image transformation algorithm combined with the weighted average processing, made use of the phase information of each sub-array, and realized the accumulation of the detection results obtained in different beams, so as to obtain a "finer" seabed track image (As shown in Fig.4), effectively improving the detection performance.

Fig.5 and Fig.6 respectively show the depth estimation results of the phase difference method of the multi-split beam and the traditional phase difference method of the split aperture. For the beam near the central region (mirror region), the traditional phase difference method fails to provide the linear part long enough to determine the zero crossing, so the depth estimation cannot be obtained. The method proposed in this paper is able to meet the detection requirements of both mirror region and non-mirror region due to the introduction of amplitude weighting factor in image transformation and the comprehensive consideration of amplitude and phase information. For edge beam detection is difficult, due to the low signal noise ratio, the traditional method of phase difference determine harder passing zero, leading to a sharp decline in detection precision, and multiple split beam phase difference detection technology with the same echo many times, at the same time, the integrated use of the automatic tracking gate algorithm and image transformation algorithm, effectively improve the detection precision of the edge of the beam.

4 CONCLUSIONS

In this paper, a submarine detection technology based on the phase difference of multi-split beam is discussed in combination with U-shaped acoustic array. The simulation and actual measurement results show that this technology is capable of detecting both mirror and non-mirror regions, and has excellent detection performance for edge beam.

References

1. LI Jiabiao. Survey Technology and Method of Multi-beam Sonar [M]. Beijing: Ocean Publication, 1999.
2. John H.S Atriano, Authony Geneva. Signal Processing for wide Swath Bathymetric Sonars [J]. IEEE, 1991: III558213-III561.
3. Luren Yang, Torfinn Taxt, and Fritz Albregtsen. "Bottom Detection for Multibeam Sonars with Active Contours ". In Proc Ocean'97, 1997:943-950
4. Fu Renqi, Hu Peng, Ding Feng, Li Ranwei. Multi-subarray seabed detection technology based on U-array [J]. Acoustics and Electronic Engineering.2010, 97(1):4-8.
5. Fu Renqi, Shen Zhengyi, Gao Bo. Survey of Maritime shipwreck With A Domestic Multi-beam System [J]. Ship Science and Technology.2015, 37(8):153-156.