Terrain Echo Signal Enhancement Technology of Marine Radar Based on Generalized Filtering

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Abstract. In order to solve the problem that the terrain echo signal of marine radar is affected by noise during transmission, which leads to poor enhancement effect, a terrain echo signal enhancement technology of marine radar based on generalized filtering is proposed. Design the graphic processing pipeline of programmable GPU, and draw the terrain echo image of marine radar. The generalized weighted median filter and Wiener filter are used to process high and low frequency signals to avoid some useful signals being filtered out. According to the high and low frequency signal processing results of the echo, the polynomial fitting sliding window is used to obtain the least square error fitting results to smooth the radar echo data. The echo signal enhancement structure is constructed, and the echo signal gain is processed to achieve the purpose of pseudo signal attenuation. Call the OpenGL read pixel function, and complete the echo signal enhancement processing according to the linear mapping relationship between the echo map and the coordinates of the DEM when processing in the GPU segment. From the experimental results, it can be seen that the echo gain effect of this technology is actually consistent, and there is only a maximum error of 1 dB between the echo signal strength and the actual data.

Keywords: Generalized Filtering · Marine Radar · Terrain Echo · Signal Enhancement

1 Introduction

Navigation radar is a commonly used equipment in ship navigation, which can detect the surrounding environment by transmitting and receiving radar waves, and obtain information about terrain, targets, and obstacles. Navigation safety is one of the most important issues in navigation. For ships, accurately identifying and analyzing terrain echo signals can help crew members predict and avoid potential collisions and dangerous situations, and improve navigation safety. However, in practical applications, the terrain echo signal of navigation radar may be affected by various factors, such as terrain complexity, changes in sea conditions, meteorological conditions, etc., resulting in a decrease in the quality of the echo signal and causing difficulties for ship navigation. In order to solve this problem, research on enhancing the terrain echo signal of maritime radar has received widespread attention.

L. Yun et al. (Eds.): ADHIP 2023, LNICST 548, pp. 100–115, 2024.
https://doi.org/10.1007/978-3-031-50546-1_7

In reference [1], an echo signal enhancement algorithm based on fuzzy logic is proposed. This algorithm constructs a membership function by extracting characteristic parameters, and sets a threshold according to this function to enhance the radar abnormal echo signal; Reference [2] proposed echo signal enhancement technology based on regional multi frame joint processing. Under the condition of strong scattering interference sources, the echo of LFMCW radar presents the phenomenon of echo signal spectrum spread outside the range. It brings serious technical challenges to radar weak target detection. Based on the correlation analysis of various components of the echo data of multiple adjacent radar beams in the center area of the detected target, through weighted compensation, the multi frame data from the scanning area near the target is used for multi frame joint processing to enhance the echo signal. Although the above two methods can enhance the radar echo signal, they are vulnerable to the influence of false signals in the signal, resulting in poor signal enhancement effect. In addition to the above methods, the following methods can also be used: (1) low-pass filters [3], bandpass filters [4], and notch filters to remove or weaken noise and interference in the echo signal. (2) Processing the echo signal in the time domain, such as smoothing, removing outliers or Outlier [5], can reduce the fluctuation and noise in the signal and make the signal clearer and more stable. (3) Processing the echo signal in the frequency domain, such as Fourier transform [6, 7], spectrum analysis, etc., can extract the frequency characteristics of the signal, further analyze and understand the signal. These methods can be selected and combined according to specific applications and needs to achieve enhancement and optimization of echo signals.

Generalized filtering can be adapted to various signal types and frequency ranges. Some signals may have complex frequency characteristics, which need to be comprehensively considered in time domain and frequency domain. Generalized filtering can capture these characteristics more accurately. For this reason, the terrain echo signal enhancement technology of marine radar based on generalized filtering is proposed. On the basis of drawing the terrain echo image of the navigation radar, the generalized filtering method is used to process the high and low frequency signals of the echo signal; Using the least squares error fitting method for data processing, and applying the terrain echo signal enhancement technology of marine radar, effective enhancement and optimization of the terrain echo signal of marine radar are achieved, improving navigation safety and ocean survey accuracy.

2 Plotting Terrain Echo Image of Marine Radar

The radar transmits an electromagnetic beam through the antenna to detect the direction and distance of the target and display it on the radar screen. The navigation radar antenna is a directional antenna. The transverse beam width of the transmitted electromagnetic wave [8] is about 2°, and the longitudinal beam width is about 20°–30°. Objects within the beam range reflect (backscatter) electromagnetic waves back to the radar antenna. The radar measures the target distance by measuring the round-trip time of the electromagnetic wave. The antenna pointing is the target orientation. When the antenna is in a certain direction, all echoes within the beam range are quantified as a sequence of echo intensity values arranged by time (distance), called scanning lines. The antenna keeps rotating, and the antenna direction changes in a circular order to complete 360° circumferential scanning. Before drawing the terrain echo image of marine radar, it is necessary to design the graphic processing pipeline of programmable GPU, as shown in Fig. 1.

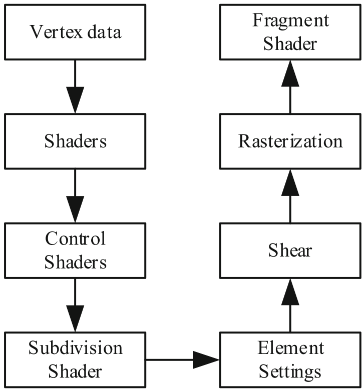


Fig. 1. Graphic processing pipeline of programmable GPU

The information such as vertex attributes and camera settings of the scene graph is sent to the vertex shader. In the vertex shader, the world coordinates, normal vector, model view transformation matrix and projection matrix of the vertex are read. The radar detection distance is the distance from the object to the antenna. If the viewpoint is set at the radar antenna, the radar detection distance is the distance from the vertex to the origin under the view coordinate system. Then the radar detection range can be calculated by formula (1):

$$l = \sqrt{x^2 + y^2 + z^2} \tag{1}$$

In formula (1), (x, y, z) Represents the apparent coordinate system. The echo intensity is related to the radar detection range and normal of the vertex, and is transmitted to the subsequent process in the form of output variables. At the end of the vertex shader, the vertex coordinates under the view coordinate system should be projected and transformed, and the vertex coordinates after the projection transformation should be assigned to the built-in variables of the vertex shader to ensure that the scene is processed according to perspective projection. Next, the GPU [9] will perform primitive assembly, cutting and rasterizing operations. Vertices are assembled into primitives and discretized into several pieces. In the slice element shader, the radar detection distance needs to be assigned to the built-in variable of the slice element shader. The reserved slice element after the depth test becomes a pixel, and the radar detection distance written to the built-in variable will eventually be written to the depth cache. In the slice shader, it is also necessary to convert the echo intensity [10] into an RGB color that can represent the echo intensity and write it into the built-in variable of the slice shader. Similarly, the color value of the reserved slice after depth testing will eventually be written into the color cache. The marine radar terrain echo image drawn from this is shown in Fig. 2.

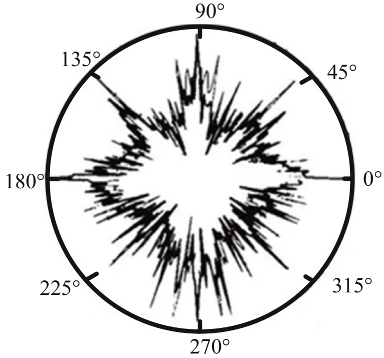


Fig. 2. Terrain echo image of navigation radar

The pixel color value is written to the scanline, which generates a scanline. Several scan lines can be generated at one time, and radar images [11] can be generated by drawing these scan lines onto the screen according to their orientations.

3 Echo High and Low Frequency Signal Processing Based on Generalized Filtering

3.1 High Frequency Signal Processing with Generalized Weighted Median Filter

In practical applications, the number of terrain echo signals from navigation radar is often large, and calculating indicators one by one through each window requires a huge amount of computation, which cannot meet the real-time requirements of signal processing. The noise points and signal details have not been effectively distinguished, and the signal quality still significantly decreases after filtering. Based on the shortcomings of weighted median filtering [12, 13], an improved adaptive weighted median filtering method is proposed to improve the noise detection and classification, noise weight determination, and noise filtering of the filtering algorithm. The improvement ideas are as follows:

The detection and classification of image noise is the premise of noise filtering [14]. The detection of noise can be divided into two steps: coarse detection and fine detection. For coarse detection, first count the number of pixels with maximum or minimum pixel value in the window. If a pixel's gray value is not extreme, it is a non noise point. Otherwise, it is a suspected noise point to be marked. The marking formula is:

$$F[I]=\begin{cases} 1, & I=255/0 \\ 0, & other \end{cases} \tag{2}$$

In formula (2): I It is the gray value of a pixel of the window point. Then fine detection is carried out. After rough detection, the image suspected noise points contain noise points and image edge details. It is necessary to further detect this. First, count the number of suspected noise points. If the gray value of a pixel of the window point is smaller than the set window size, the suspected noise points in the window can be filtered as noise points; Otherwise, increase the window size and continue to judge until the requirements are met.

After noise detection and classification, image noise is basically detected and marked. If median filtering is directly applied to noise points, "overfiltering" will occur. To overcome this phenomenon, remove the number of noise points in the window, multiply the gray values of the other non noise points by the weight values, and then sort the size on this basis to get a new set of sequences and take the value, that is, the output value of the window's central pixel can be expressed as formula (3):

$$I{=}Med\left\{\frac{1}{a^2}g_0(k-m),\cdots,\frac{1}{a^2}g_m\big(k-m+m'\big)\right\} \tag{3}$$

In formula (3), $g_0(k-m),\cdots,g_m\big(k-m+m'\big)$ Assign values to each pixel in the window; m' Indicates the number of noise points; a Indicates the size of the filtering window; k Indicates window sorting.

Combine the formula to output the filtering results, continue to migrate the filtering template, and complete the overall image filtering.

3.2 Generalized Adaptive Wiener Filtering Low Frequency Signal Processing

Wiener filter [15] can filter image noise by assuming that the noise image signal is the sum of image signal and noise signal, and the second-order statistical characteristics of both are known. The filter parameters can be obtained according to the relevant error criteria, which can be expressed as formula (4):

$$E = D(b,h) - \xi \cdot F(b,h) \tag{4}$$

In formula (4), $D(b,h)$ Represents the b that 's ok h Image signal of the column; $F(b,h)$ Represents noise signal; ξ Is the Wiener filter, which can be expressed as Formula (5):

$$\xi = \frac{F^2(b,h) - \sigma^2}{F^2(b,h)} \tag{5}$$

In formula (5), σ^2 Represents the noise pixel variance value. The adaptive Wiener filter is used to filter the low-frequency sub image in the wavelet domain. Although the low-frequency image contains most of the image information, it is basically not affected by noise. The noise pollution degree of low-frequency sub image in wavelet domain is relatively light, but it can not be ignored. An improved adaptive Wiener filter potential for this part of image will retain a lot of useful information.

3.3 Fitting Based on Least Squares Error

According to the high and low frequency signal processing results of the echo, the formula (6) can be obtained by adding a sliding window to the data at all range points of the radar echo at a certain time:

$$C_a^t[l] = o - a,\cdots,o + a \tag{6}$$

In formula (6), l Represents distance; o Represents the center of the sliding window. Combined with the generalized filtering processing results, the sliding window is polynomial fitted according to formula (7):

$$C[l] = \sum_{z=0}^{o} \eta_z l^z \tag{7}$$

In formula (7), η Represents the polynomial coefficient; z Indicates the degree of the polynomial. Based on this, the result of least square error fitting is Formula (8):

$$\vartheta_z = \sum_{z=0}^{o+a} \left(C[l] - C_a^t[l]\right)^2 \tag{8}$$

According to the basic principle of calculus ϑ_z Then, the original data is characterized by Eq. (7), and all fitting points of the original echo data are obtained by moving the sliding window from front to back. Because the clutter and noise data deviating from the polynomial curve will be discarded in the fitting process, this method can smooth the radar echo data in the range.

4 Terrain Echo Signal Enhancement Technology of Marine Radar

4.1 Echo Signal Enhancement Structure Design

The traditional radar simulator image generation mostly uses the scanning line intersection algorithm to calculate all echo polygons within the range and draw them to video memory. The scanning effect of the radar simulator is achieved through OpenGL template cache. A small angle sector area is drawn with the ship's position as the center and the range as the radius as the template. Only the echoes overlapped with the sector template can be seen in video memory. The center angle position of the sector template changes at a certain speed to form a dynamic scanning picture. This mechanism will increase the redundant operation of the computer CPU to a certain extent, which is specifically shown in the following two aspects:

(1) A small scanning angle is smaller than the whole scene, but when judging echo occlusion, it needs to calculate the distance, angle and other imaging geometric information of all polygons in the scene, which results in a large amount of redundant calculation.
(2) When using DEM to enhance echo image, it is necessary to overcome the influence of latitude gradual growth rate. As long as the image is divided into multiple regions in latitude, the energy accumulation of adjacent regions will be incomplete during echo calculation. It is necessary to overlap a small part of adjacent regional echoes, which will also generate redundant calculation.

As the resolution increases and the radar range increases, the amount of echo data that needs to be simulated increases sharply. The echo signal enhancement structure built based on this is shown in Fig. 3.

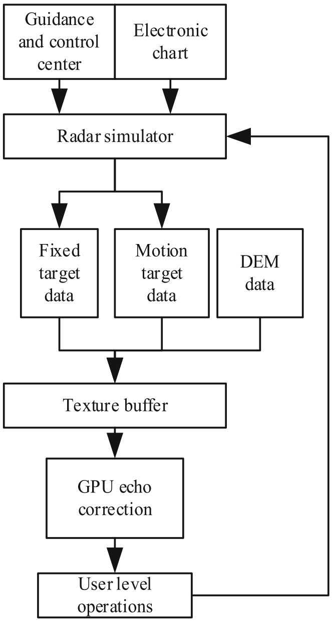


Fig. 3. Echo signal enhancement structure

Read the electronic chart data of the target area, store the contour lines as a linked list, store the longitude and latitude boundary, the ship's information, and radar parameters given by the guidance and control center to the radar simulator, and transfer the longitude and latitude boundary, the ship's information, and radar parameters to the GPU constant register; The DEM data in this area is stored in the GPU texture buffer to facilitate subsequent processing.

4.2 High and Low Frequency Echo Signal Gain

The terrain echo signal of marine radar is formed by nonlinear coupling of two high and low frequency echo signals. If periodic signals, noise sources and nonlinear bistable systems match each other, stochastic resonance can be generated. The three-dimensional diagram of nonlinear coupling potential function of the echo signal is shown in Fig. 4.

As the high and low frequency echo signals are continuously added to the weak periodic signals, the echo signals will change periodically and lose balance. Under the action of the driving force, the potential function will also change, and the potential barrier at the central height will also change differently. However, the energy of Brownian particles is too small due to the weak energy of periodic signals in the process of motion. With the continuous addition of noise, the energy of Brownian particles increases, making them quickly cross the barrier to reach another potential well within the range of a single potential well. At this time, the stochastic resonance phenomenon occurs when the movement period is consistent with the weak signal period.Because the nonlinear coupling potential function of the echo signal is affected by the nonlinear coupling

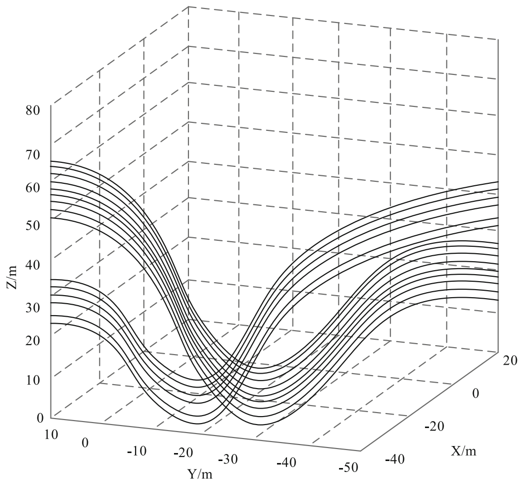


Fig. 4. 3D Diagram of Nonlinear Coupling Potential Function of Echo Signal

coefficient, the periodic signal and the noise motion direction should be in the same direction under the action of the driving force, which can generate appropriate nonlinear coupling coefficient.

When the nonlinear coupling coefficient is determined, the signal is processed with gain, as shown in Formula (9):

$$SF(A,B) = \int_{-\infty}^{+\infty} x(A)x(B)H(D)\exp(-2\pi t)dt \tag{9}$$

In formula (9), $x(A)$, $x(B)$ Represent the time domain of high-frequency and low-frequency signals respectively; $H(D)$ Indicates the width of the emitted electromagnetic wave. If a certain time point in the time domain of a signal to be analyzed t Characteristics research, through t After signal gain processing at time point, the purpose of pseudo signal attenuation can be achieved.

4.3 Echo Signal Enhancement Processing

Call OpenGL's read pixel function to read the color value of the scene from the computer's graphics card memory and save it to the texture buffer; Read the echo drawn at the current time, that is, capture the width and height of the screen, data format and type, and store them in the GPU texture buffer. The ship's position is updated in real time by the data transmitted from the guidance and control center. The rectangular coordinate system is the tangent plane of the point. Within the radar range, the radar echo coincides with a small area of the DEM. The geographical coordinates of the DEM echo image in the texture buffer are projected and clipped to a rectangle on the screen coordinates, and the coordinate mapping of the two images is calculated in the horizontal and vertical directions. When the echo image and the DEM are processed in the GPU segment, the coordinate linear mapping relationship is as follows (10):

$$\begin{cases} x_a = \alpha_1 x_e + \beta_1 \\ y_a = \alpha_2 y_e + \beta_2 \end{cases} \tag{10}$$

In formula (10), (x_e, y_e) Represents radar echo coordinates; (x_a, y_a) Represents radar DEM coordinates; $\alpha_1,\ \alpha_2$ Represent horizontal and vertical coordinate conversion coefficient respectively; $\beta_1,\ \beta_2$ Represents the horizontal and vertical coordinate conversion random number.

Due to the influence of latitude gradual growth rate, the geographical distance represented by each pixel on the vertical axis of DEM data increases with the increase of latitude. The echo image to be corrected is divided into rectangular areas with equal pixels on the vertical axis, and the influence of latitude gradual growth rate is eliminated according to formula (10); The greater the number of rectangular area partitions, the more accurate the latitude of DEM data correction. But to ensure the calculation speed, $\alpha_1,\ \alpha_2, \beta_1,\ \beta_2$ It can be expressed by the following formula:

$$\begin{cases} \alpha_1 = \frac{x_h - x_0}{x'_h - x'_0} \\ \alpha_2 = \frac{y_h - y_0}{y'_h - y'_0} \end{cases} \tag{11}$$

$$\begin{cases} \beta_1 = x_0 - x'_0 \alpha_1 \\ \beta_2 = y_0 - y'_0 \alpha_2 \end{cases} \tag{12}$$

In the above formula, (x_h, y_h), $\left(x'_h, y'_h\right)$ Represent the coordinates of the lower right corner of the echo map range and the lower right corner of the echo map corresponding to the DEM respectively; (x_0, y_0), $\left(x'_0, y'_0\right)$ Represent the ship's DEM coordinates and echo map coordinates respectively. Criteria for echo image enhancement with DEM data: pixels without DEM echo data can generate echo only when the radar scans the marked artificial buildings; There are echo pixels in both DEM and radar, and the gray value of DEM is multiplied by the echo value for correction: DEM has echo data but radar has no echo, and DEM pixels are used to modify the contour boundary of radar echo; After image enhancement, the radar echo image is modified from the original irregular quadrilateral binary image to the radar echo image filled with gray value. The larger the gray value, the higher the elevation, indicating the better the echo enhancement effect.

5 Experiment and Analysis

5.1 Design of Signal Capture Structure Experimental Platform

The experimental signal capture is carried out on the LabVIEW platform, and its structure is shown in Fig. 5.

The structure shown in Fig. 5 is mainly used to receive signal center frequency, level and storage data duration. Through this platform, the application effectiveness of terrain echo signal enhancement technology of navigation radar based on generalized filtering is verified. Analyze the received echo signal and demodulate the radar electromagnetic wave.

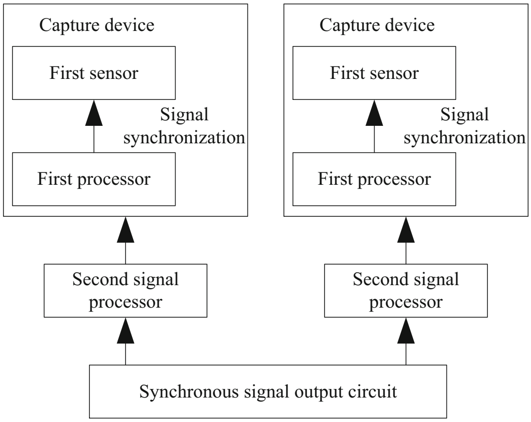


Fig. 5. Signal Capture Structure Experiment Platform

5.2 Experimental Process Simulation

Two experimental situations are set. One is that when no signal is received or the signal is blocked, the platform will first check the pending table after executing the OS code. The pending table can be used to analyze whether a signal is received. If not, return to the user status and execute the next code.

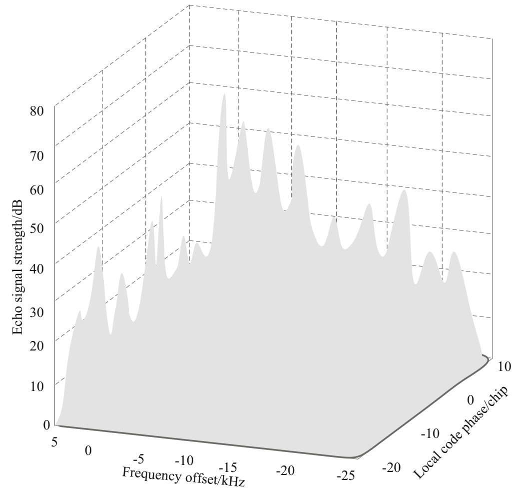
(a) Situation 1 (b) Situation II

Fig. 6. Echo gain in two cases

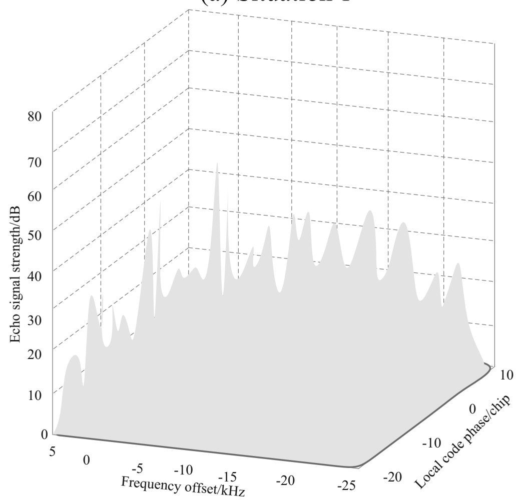
Case 2: When a signal is received and the signal is not blocked, the second position in the pending table will change after the platform executes the OS code. Assume that the received signal is No. 2. After executing the OS code, check the pending table. If the received signal is found, check the block table. If signal 2 is blocked, it will return to user mode as above; If it is not blocked, the corresponding processing function will be executed.

5.3 Analysis of Experimental Data

The data used in the experiment was sourced from the RADARSAT Geophysical Processor System (RGPS) dataset. This data includes a wide range of terrain and ocean application scenarios, such as landform measurement, glacier monitoring, and ocean storm observation. By using radar echo signals, surface elevation, surface coverage type, water body boundaries, and other geographic information can be obtained.



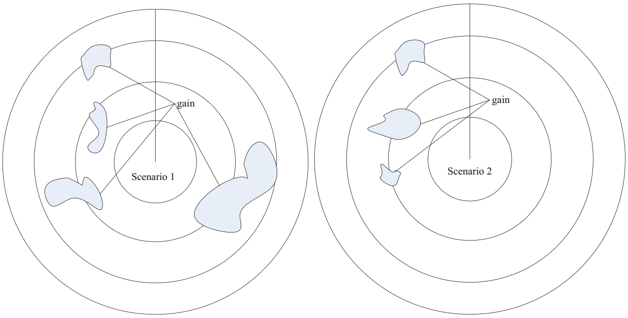
(a) Situation 1



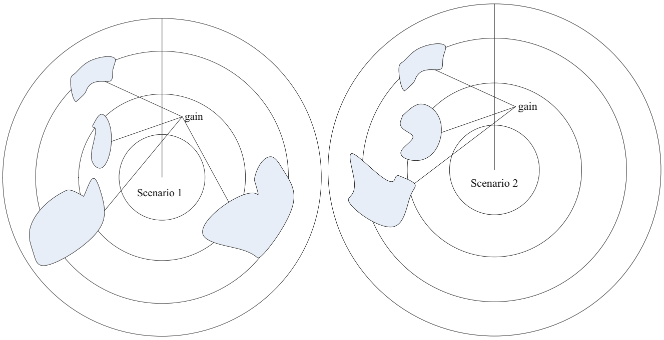
(b) Situation II

Fig. 7. Terrain echo signal enhancement results of navigation radar

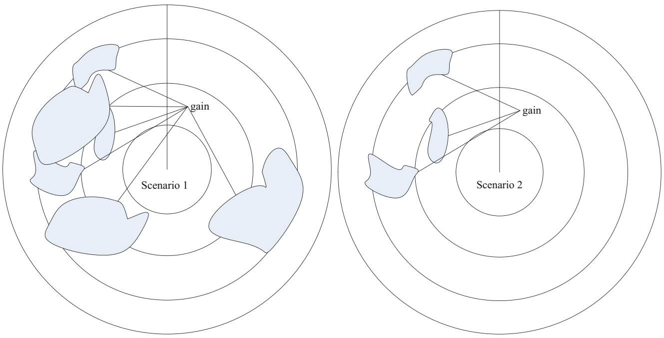
In order to verify the reliability of the terrain echo signal enhancement technology of navigation radar based on generalized filtering, the echo gain in two cases is analyzed, as shown in Fig. 6.



(a) Fuzzy logic



(b) Regional multi frame joint processing



(c) Generalized filtering enhancement

Fig. 8. Echo Gain Comparison Results of Three Methods

It can be seen from Fig. 6 that the echo gain in case 1 is larger than that in case 2, which means that the weaker the echo signal is, the greater the echo enhancement will be.

According to the echo gain in Fig. 6, the terrain echo signal enhancement results of navigation radar under ideal conditions are obtained, as shown in Fig. 7.

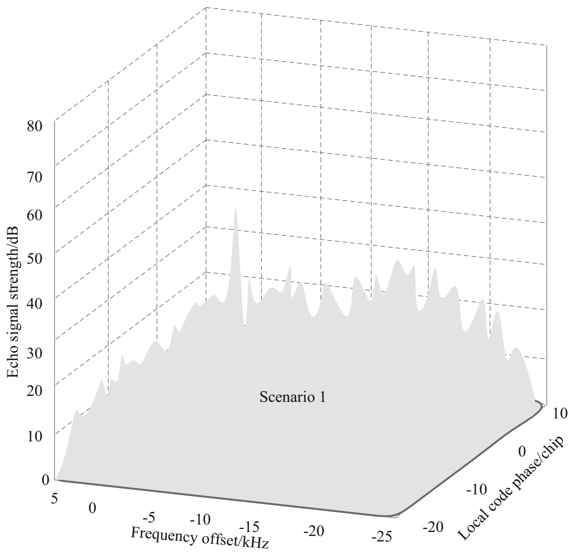
It can be seen from Fig. 7 that the maximum echo signal strength in case 1 is 55 dB, and the maximum echo signal strength in case 2 is 42 dB.

5.4 Experimental Results and Analysis

Taking the echo gain in Fig. 6 as a reference, the echo signal enhancement algorithm based on fuzzy logic, the echo signal enhancement technology based on regional multi frame joint processing and the echo signal enhancement technology based on generalized filtering are used to compare and analyze the echo gain. The comparison results are shown in Fig. 8.

It can be seen from Fig. 8 that the echo signal enhancement algorithm based on fuzzy logic and the echo signal enhancement technology based on regional multi frame joint processing are inconsistent with the actual echo gain effect, while the echo signal enhancement technology based on generalized filtering is consistent with the actual echo gain effect.

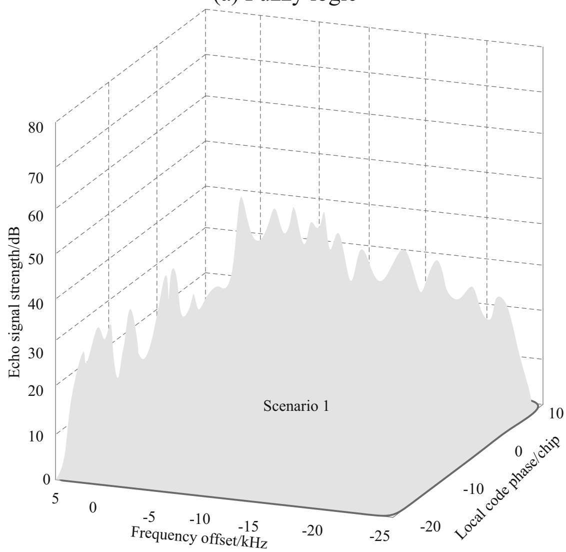
Using the echo gain in Fig. 7 as a reference, these three methods are used to compare and analyze the echo signal enhancement effect, as shown in Fig. 9.

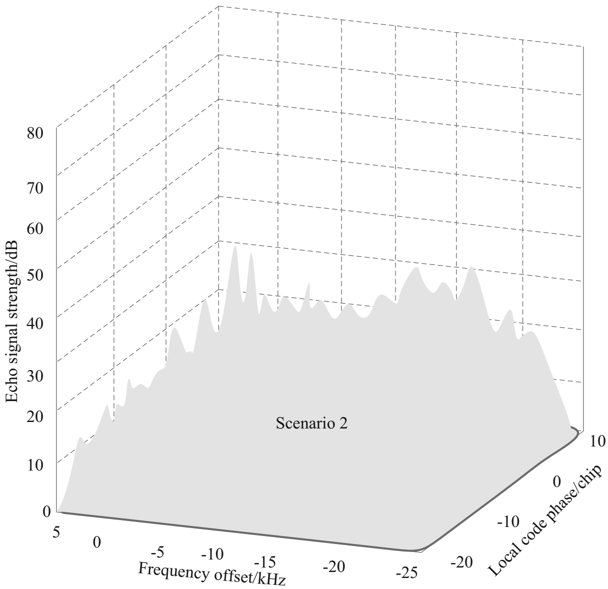


(a) Fuzzy logic

Fig. 9. Signal radar acquisition comparison results of three methods

(a) Fuzzy logic

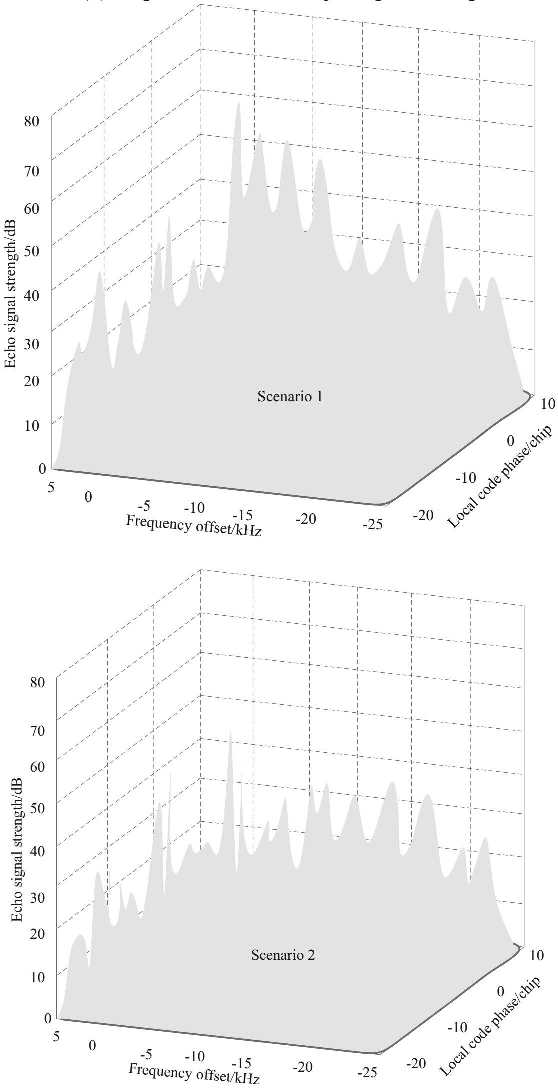




(b) Regional multi frame joint processing

Fig. 9. (*continued*)

(b) Regional multi frame joint processing



(c) Generalized filtering enhancement

Fig. 9. (*continued*)

It can be seen from Fig. 9 (a) that the maximum echo signal strength in case 1 is 35 dB, and the maximum echo signal strength in case 2 is 23 dB; It can be seen from Fig. 9 (b) that the maximum echo signal strength in case 1 is 38 dB, and the maximum echo signal strength in case 2 is 39 dB; It can be seen from Fig. 9 (c) that the maximum echo signal strength in case 1 is 55 dB, and the maximum echo signal strength in case 2 is 41 dB. Only this method has a maximum error of 1 dB with the actual data.

6 Conclusion

At present, there is a problem of poor echo signal enhancement effect in the research of radar echo signal enhancement processing methods. In order to solve this problem, a marine radar terrain echo signal enhancement technology based on generalized filtering is proposed. This technology uses generalized filtering and multinomial least square fitting to smooth clutter and noise in the echo, At the same time, the weak details of the target echo are effectively retained. On this basis, combined with the background removal, low-pass filtering and other processing in the time dimension, the radar echo signal can be enhanced.

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