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THE RESEARCH ON OCEAN CURRENT INVERSION ALGORITHM BASED ON X-BAND RADAR

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Abstract. *In order to overcome the problem that the traditional X-band radar is not known in the process of constructing the dispersion-related band-pass filter, a dispersion model extraction method is proposed, and the algorithm is improved. Firstly, a rough dispersion relation model is constructed for the different energy characteristics of the radar image in the radar image. Then the inversion equation is used to obtain the initial velocity and the band-pass filter is constructed. The real wave spectrum is obtained by using the band-pass filter to get the real wave spectrum. Finally, the weighted wave method is used to estimate the flow spectrum and the results are satisfactory. The experimental results show that the improved algorithm can make up the shortcomings of the traditional algorithms, and has high accuracy, stability and good application value.*

Keywords: Ocean current inversion, Dispersion relation model, Filtering, Least square method, Iterative estimation

1. **Introduction.** Sea surface current is large-scale stable seawater flow on the surface of the sea water which is formed by the different density of adjacent water group or it is due to the effect of wind, geomagnetism or deflective force [1]. Sea surface current information is useful for off-shore navigation and maritime construction and it is also a most important resource for civil and military purposes. Meanwhile, the precise inversion of the velocity is the premise inversion conditions of wave height, sea surface wind and other current information.

Traditionally, people usually measure the current flow by setting buoy or using measure instruments. Although this method can get the ocean flow information, it is easy to be damaged and has other defects and limitations. In order to overcome the above problems, marine-based X-band radar remote sensing technology is into the horizon. X-band radar images can detect sea target. Meanwhile, when radar electromagnetic waves are irradiated onto the sea surface, it can cause Bragg scattering, and then the resulting radar echo is displayed as a sea clutter image, which contains a wealth of waves information, so it is an important way to research the ocean parameters. Many people in the world have done lots of work to improve the accuracy of the inversion [1]. In 1985, Young et al. used the least squares method to reflect the sea currents and waves information [2]. In 2001, Senet et al. proposed an iterative estimation algorithm based on Young's velocity inversion theory and it was greatly improved by iterating the results of the previous estimation process to the next estimation process [3]. In 2002, Gangeskar researched on the angle of least squares method and considered that the energy of different image spectrum in the process of inverting was not the same level. Then he proposed iterative least squares estimation of velocity taking the image spectrum energy as the weight [4]. In 2010, Serafino et al. developed a new way of the current flow algorithm based on the normalized scalar product algorithm of the estimated flow [5]. In 2011, Shen et al. designed the band-pass filter to filter out the noise in the image data based on the way of Gangekar, which further improved the accuracy of inversion [6]. In 2013, Ludeno et al. improved the normalized scalar product estimation method and used this way on ocean bathymetry [7]. In 2015, Wang et al. proposed a pre filtering algorithm based on geometric model [8].

The sea clutter image has much noise and it is also influenced by many factors. So, the low purity of the wave spectrum makes the inversion result less accurate. We cannot construct an accurate filter when we do not know the reference velocity. As a result of that we cannot guarantee the accurate inversion. So we need a new way to improve the accuracy.

In this paper, a new strategy of dispersion relation model extraction from X-band marine radar images is presented. In traditional way, the current parameters need to be selected by experience and then construct a dispersion relation band-pass filter, which may not be accurate. The algorithm proposed here can get the primary current information and then construct a more accurate filter to improve the accuracy of inversion. The traditional ocean current inversion algorithm is explained in detail in Section 2. In Section 3, the improved inversion algorithm is presented in detail and it is also the core of this paper. In Section 4, the experiment and analysis have done to test the new algorithm. A summary and a few constraints on the algorithm appear in Section 5.

2. **Traditional Ocean Current Inversion Algorithm.**

2.1. **Dispersion relationship.** The volatility caused by gravity becomes a gravity wave, and it is clear that the sea surface wave is one of the gravity waves [9]. Therefore, according to the linear wave theory, the wavelength and period of the sea surface wave proximately accord with the basic dispersion relation equation. The equation of dispersion is given by the following equation [10].

$$\omega\left(\overrightarrow{k}\right) = \sqrt{gk\tanh(kd)} \tag{1}$$

Among them, ω is the wave frequency; g is the gravitational acceleration; k is the wave vector; d is the water depth. When there is a flow velocity in the sea, the Doppler shift is introduced into the dispersion relation equation due to the relative motion between the radar and the sea surface wave. The dispersion equation is changed to the following equation.

$$\omega\left(\overrightarrow{k}\right) = \sqrt{gk\tanh(kd)} + \overrightarrow{k}\cdot\overrightarrow{U} \tag{2}$$

Among them, $\overrightarrow{U}$ is the relative velocity vector. When the radar is stationary, it is the sea surface velocity vector. In order to show the effect of Doppler shift on the wave frequency of the dispersion equation, the following graphs show the image of the wavenumber frequency domain with no velocity in dispersion relation and the image with velocity.

What can be seen from Figure 1 is that the dispersion relation surface had deformation from the symmetry plane on the direction of the relative velocity, and a no-velocity circle with 0 circles turned into ellipse on the two-dimensional projection of wavenumber plane.

2.2. **Band-pass filter.** From the linear wave theory, most of the wave spectrum in the radar image should fall on the following basic dispersion relation surface, and the noise spectrum does not have this characteristic [6]. According to this principle, we can make the dispersion band-pass filter to filter out the noise. The following is the specific construction process.

1) When the depth of water is large, $\tanh(kd) \approx 1$, and the dispersion equation is obtained by deformation:

$$\omega = \sqrt{g|k|} + |k|\cdot|U|\cos(\theta) \tag{3}$$

Among them, $|k|$ is wave number mode; $|U|$ is velocity mode; θ is the angle between wave number and flow direction.

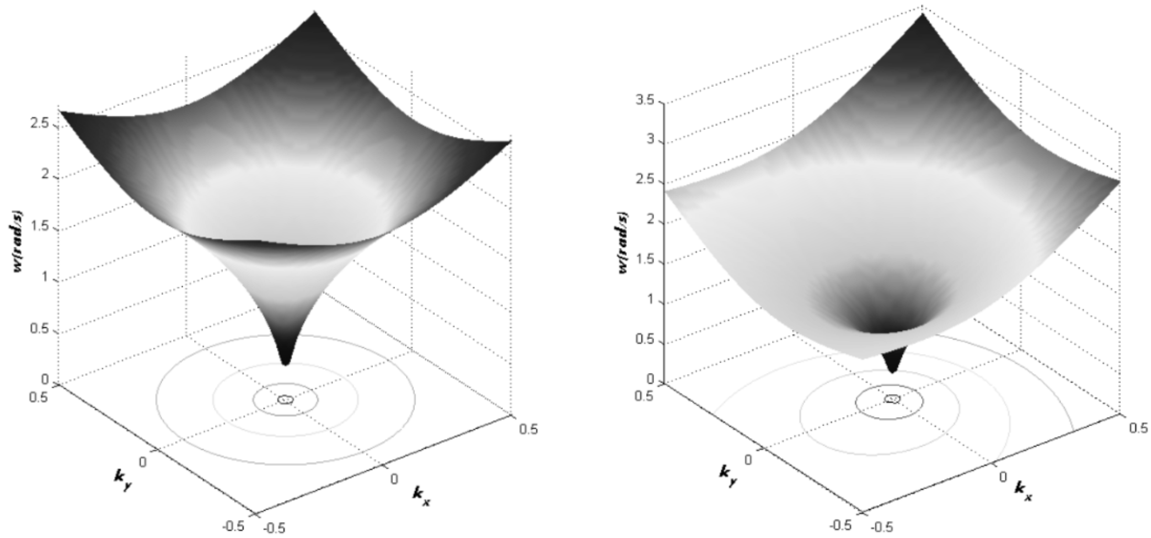

Figure 1. Dispersion relation shell

2) Let $\cos(\theta) = -1$ to get the upper edge of the filter. Considering the influence of wave number resolution and frequency resolution, we can get the following form after transforming Formula (3):

$$\omega + \frac{\Delta\omega}{2} + |k_m| \cdot |U| \geq \sqrt{g\left(|k| - \frac{\Delta k}{\sqrt{2}}\right)} \tag{4}$$

Among them, Δk is wave number resolution and $\Delta\omega$ is frequency resolution; $|k_m|$ is the main guided waves mode whose number is maximum, whose wave is obvious and whose echo signal is the strongest. $|U|$ is the flow velocity mode and then we can derive the upper edge of the filter:

$$|k_p| = \frac{\left(\omega + \frac{\Delta\omega}{2} + |k_m| \cdot |U|\right)^2}{g} + \frac{\Delta k}{\sqrt{2}} \tag{5}$$

Among them, $|k_p|$ is the upper boundary of the dispersion relation band-pass filter.

3) In the same way, we can suppose $\cos(\theta) = 1$, and then derive the lower boundary of the filter, which is similar to the upper boundary derivation method. The lower boundary is the following:

$$|k_n| = \frac{\left(\omega - \frac{\Delta\omega}{2} - |k_m| \cdot |U|\right)^2}{g} - \frac{\Delta k}{\sqrt{2}} \tag{6}$$

Then the final filter model is:

$$F^{(3)}(K,\omega) = \begin{cases} I^{(3)}(k,\omega), & |k| \in [|k_n|, |k_p|] \\ 0, & \text{Others} \end{cases} \tag{7}$$

Among them, $I^{(3)}(k,\omega)$ is the image spectrum, and $F^{(3)}(k,\omega)$ is the wave spectrum after filtering. Since the flow velocity U in the band-pass filter is unknown, it is usually replaced by the historical maximum flow velocity in the inversion area in practical applications. If people cannot get the largest flow velocity, they need to select according to experience, which can make the filter boundary too wide, resulting in error.

2.3. **Ocean current inversion formula.** After ocean wave spectrum is filtered, we can use the weighted least squares method to realize the ocean current inversion. According to the minimum principle, we can take the most suitable weighted variance:

$$Q^2 = \sum_{i=1}^{n_0} \left(\omega_i - \omega\left(k_i\right)\right)^2 E\left(k_{xi}, k_{yi}, \omega\left(k_i\right)\right) \tag{8}$$

Among them, ω_i is the wave of the i-th theoretical frequency; $\omega\left(k_i\right)$ is the measured frequency which is calculated based on the obtained dispersion relation model; $E\left(k_{xi}, k_{yi}, \omega\left(k_i\right)\right)$ represents the power value corresponding to the wavenumber; n_0 is the number of points contained in the dispersion relation model.

In order to find the best velocity component u_x and u_y, the cost function needs to be minimized, and then take partial derivative of u_x and u_y with respect to Q^2 respectively, and make the results equal to zero. Finally, we can derive the flow velocity formula:

$$\begin{bmatrix} u_x \\ u_y \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n_o} k_{xi}^2 E & \sum_{i=1}^{n_o} k_{xi}k_{yi}E \\ \sum_{i=1}^{n_o} k_{xi}k_{yi}E & \sum_{i=1}^{n_o} k_{yi}^2 E \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{n_o} k_{xi}\omega(k_i)E \\ \sum_{i=1}^{n_o} k_{yi}\omega(k_i)E \end{bmatrix} \tag{9}$$

Among them, u_x and u_y are the component of flow velocity; E is the power value $E(k_{xi}, k_{yi}, \omega(k_i))$, and other variables are the same as before.

3. Improved Inversion Algorithm.

3.1. **The extraction of dispersion relation mode.** Building a band-pass filter requires obtaining current velocity information as a parameter, which is contradictory to the ultimate aim of the filter for ocean current inversion. In this paper, we proposed a method to construct the dispersion relation model to obtain the initial current velocity to build the band-pass filter.

In theory, there is a dispersion relation equation corresponding to one of ω_k for any points (k_{xi}, k_{yj}) in the plane of wave number, and the image spectrum with the wave information is corresponding to the spectrum of the point $(k_{xi}, k_{yi}, \omega_k)$ in three-dimensional frequency space of wave number [11]. To extract the wave spectrum that meets the above requirements, we should do the following steps to improve the image spectrum data.

1) In order to eliminate the influence of non-homogeneous and inhomogeneous energy spectrum on the subsequent filtering and inversion results, we can build the high-pass filter to filter high-frequency wave. The filter is as follows:

$$I_1^{(3)}\left(k_x, k_y, \omega\right) = \begin{cases} 0, & \omega < \omega_{cut} \\ I_0^{(3)}\left(k_x, k_y, \omega\right), & \omega \geq \omega_{cut} \end{cases} \tag{10}$$

Among them, ω_{cut} is cutoff frequency, and it is usually $0.03 * 2\pi$ radian/s based on experience.

2) For any point (k_{xi}, k_{yj}) in the plane of the wave number, there is a column vector along the direction of ω, which can be expressed as $I_1^{(3)}\left(k_{xi}, k_{yj}, \omega_k\right)$, $k = 1, \ldots, 32$. Then find the point where the spectrum energy is the most in this vector. A corresponding threshold $\overline{P}$ is set to find out whether it belongs to the wave spectrum or the noise. When the maximum value of the spectrum energy is less than this threshold, the elements of the current column vector points are excluded in the subsequent calculations, and all points are assigned to 0.

We can see in the following formula:

$$I_2^{(3)}\left(k_{xi}, k_{yj}, \omega\right) = \begin{cases} 0, & I_1^{(3)}\left(k_{xi}, k_{yj}, \omega\right)|_{\max} < \overline{P} \\ I_1^{(3)}\left(k_{xi}, k_{yj}, \omega\right), & I_1^{(3)}\left(k_{xi}, k_{yj}, \omega\right)|_{\max} \geq \overline{P} \end{cases} \tag{11}$$

Among them, $I_1^{(3)}(k_{xi}, k_{yj}, \omega)|_{\max}$ is the maximum value of column vectors. $\overline{P}$ is the threshold for dividing the noise and the wave spectrum and it is critical to select its value. If it is too low, it is possible to have noise in the subsequent filtering and inversion process. And if it is too high, it may exclude the wave spectrum that contains the information of waves, which can impact the inversion accuracy [8]. According to a large number of data analysis, the threshold can be gotten in the following formula:

$$\overline{P} = I_1^{(3)}(k_x, k_y, \omega)|_{\max}/2000 \tag{12}$$

Among them, $I_1^{(3)}(k_x, k_y, \omega)|_{\max}$ is the maximum value of all the image spectrum.

3) According to the previous analysis, there is only one frequency corresponding to the dispersion relation model for column vector along the ω axis direction in the wave number plane, which is related to the wave spectrum. We calculate derivation of all the points and extract the peak of the column vector in the image spectrum to determine ω_k. When the peak is a single peak, as shown in Figure 2, there are no other peaks in the column vector that exceed three of the maximum peak energy, and the frequency corresponding to this peak image spectrum is ω_k, which is on the dispersion relationship model. If the waveform is a non-single peak, as shown in Figure 3, the energy waveform is displayed as a number of irregular peaks, indicating the presence of noise making the waveform serious distortion. In this case, ω_k will be set to 0.

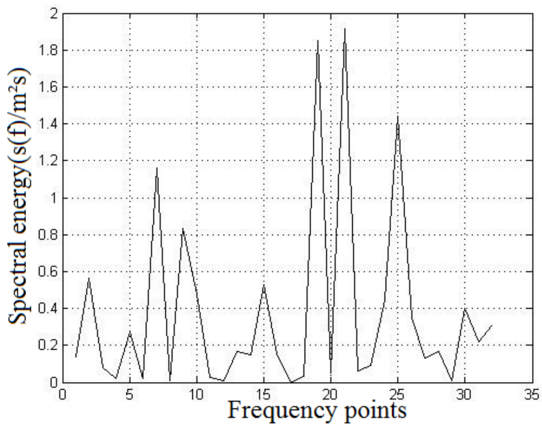

Figure 2. Single peak waveform

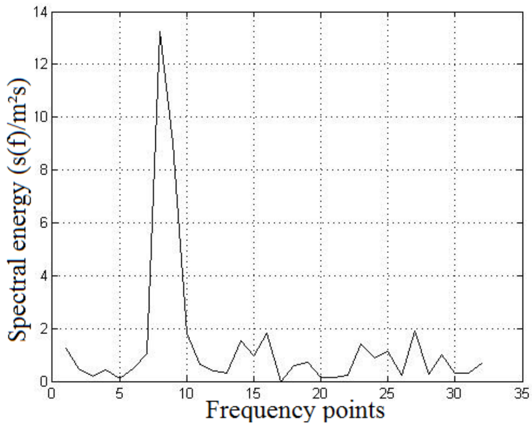

Figure 3. Multi peak waveform

The frequency of the dispersion relation is obtained from the total angular frequency column vector in the image sequence. Then we can put the frequency and the corresponding spectral energy together to obtain a $128 * 128 * 32$ three-dimensional matrix, and all non-zero elements in this matrix can be regarded as a rough dispersion relation model.

3.2. **The improved inversion process.** The improved algorithm is shown in Figure 4, and Figure 5 shows the X-band radar image.

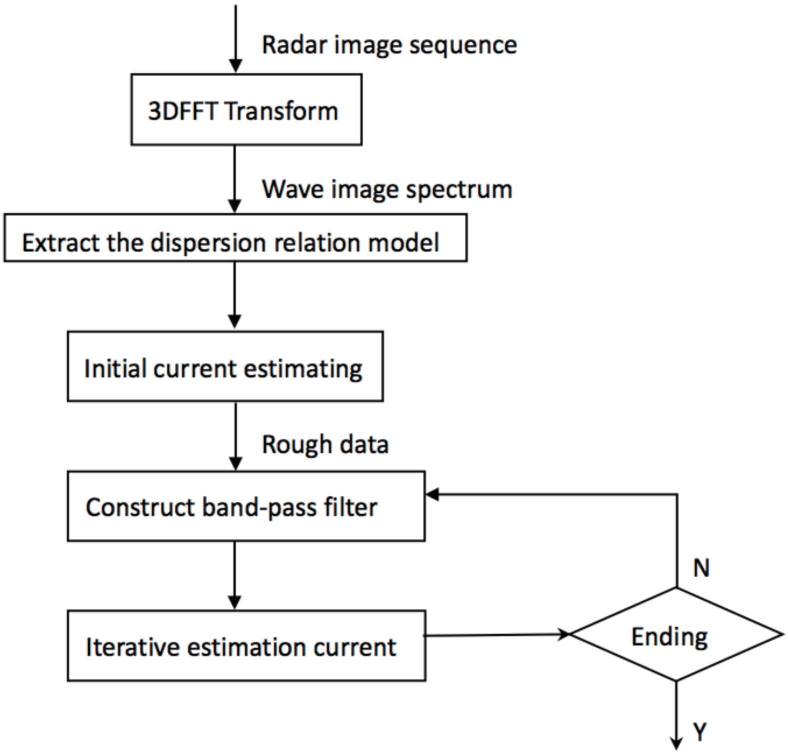

FIGURE 4. Inversion flow chart

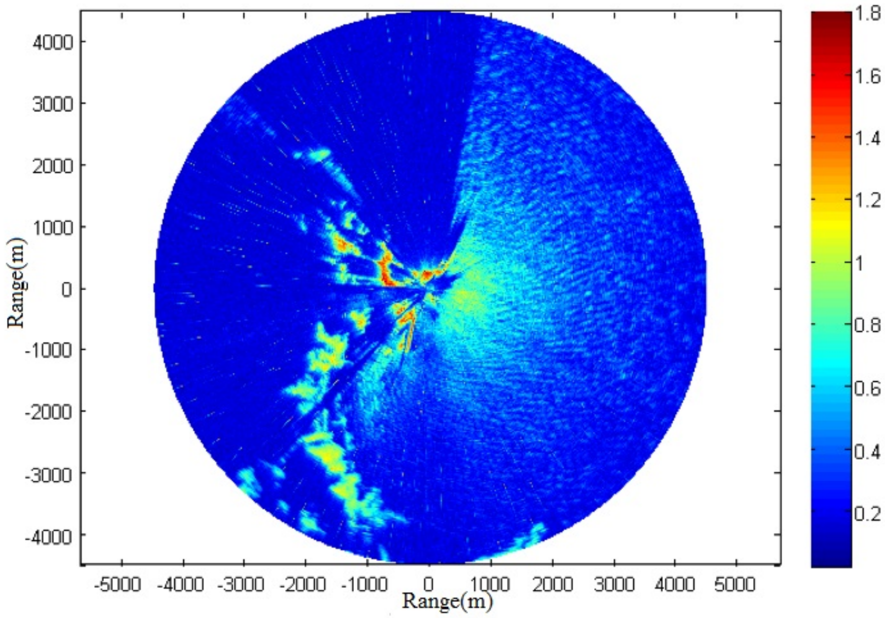

FIGURE 5. X-band radar image

1) Extract the dispersion relation model: According to the method proposed in Section 3.1, the wave spectrum in accord with the dispersion relation model is extracted from the image spectrum obtained by Fourier transform, and then put it in Formula (9) to get a rough current information.

2) Build band-pass filter: Band-pass filter can be constructed according to Section 2.2 based on the information of the initial estimated flow. Re-filter the data, and re-use the current inversion formula to obtain new ocean current information.

3) Iterative flow estimate: It should determine whether the iterative process is over. The project usually has about 10 times iteration to meet the accuracy requirements. If the iteration is not over, repeat the previous step and put the information obtained in the previous step into the current inversion formula to extract more accurate current information. If the iteration ends, exit the loop and output the current.

Compared with the traditional inversion process, the improved algorithm extracts a dispersion relation model from the image sequence according to the energy characteristics of the wave spectrum, and all the elements are in accordance with the dispersion relationship. Then it can get an initial flow velocity information through inversion and it can be used to construct a band-pass filter. The traditional method of band-pass filter construction process depends on selecting the possible maximum flow velocity by experience, causing error. However, the improved algorithm can solve this problem.

4. **Experiment and Analysis.**

4.1. **Experimental data.**

The experimental site is Haitan Island, Pingtan County, Fujian Province. The island is located in the northern island of Taiwan. Figure 5 shows the sea clutter image sequence collected by X-band radar at 10 am on October 22, 2010. Each image sequence contains 32 maps covering a radius of approximately 2km. Radar position is 40m higher than the sea surface and the rotation time is about 2s. Considering the distance between the terrain and shore, the sub-image interception area is an ideal area in the 75° direction, and the size is 128×128 pixels (7.5m between two pixels). Experiments were carried out by using traditional dispersion filters and the proposed method in this paper.

4.2. **Experimental results and analysis.**

We used the ocean wave detection equipment WAVEX to get the current information as a reference. Figure 6 shows the current velocity contrast diagram obtained by the inversion of the pre and post algorithm, and the current direction contrast diagram is shown in Figure 7.

The results are satisfactory. In Figure 6, the red crossed solid line represents the inversion result of the traditional inversion method; the green asterisk solid line represents the improved algorithm inversion result, and the blue cross solid line indicates the result of the WAVEX device. From the comparison results in Table 1 we can know that the improved algorithm is closer to the reference flow velocity compared with the traditional method, and the average error down to 0.17 compared with 0.38 from the original method. The mean-square deviation is improved to 0.41 while it is 0.53 in the original method. It shows that the improved method is better than the traditional methods and it is more stable and accurate.

In Figure 7, the red crossed solid line represents the result of the current direction in the traditional inversion method; the solid line of the green asterisk represents the result of the improved algorithm; the blue cross solid line represents the result of the current direction as a reference. From Table 1, we can know that the improved algorithm is more accurate than the traditional method in the aspect of current direction inversion and the average error is down to 2.15. Moreover, the standard deviation is ranging from 18.51 to 28.16. It is obvious that the improved method improved both in stability and accuracy.

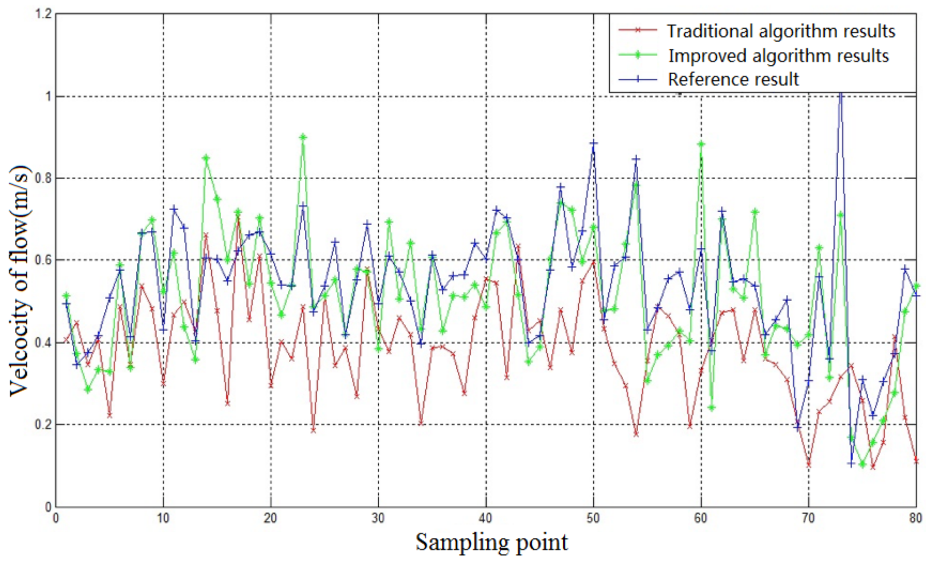

FIGURE 6. Current velocity contrast diagram

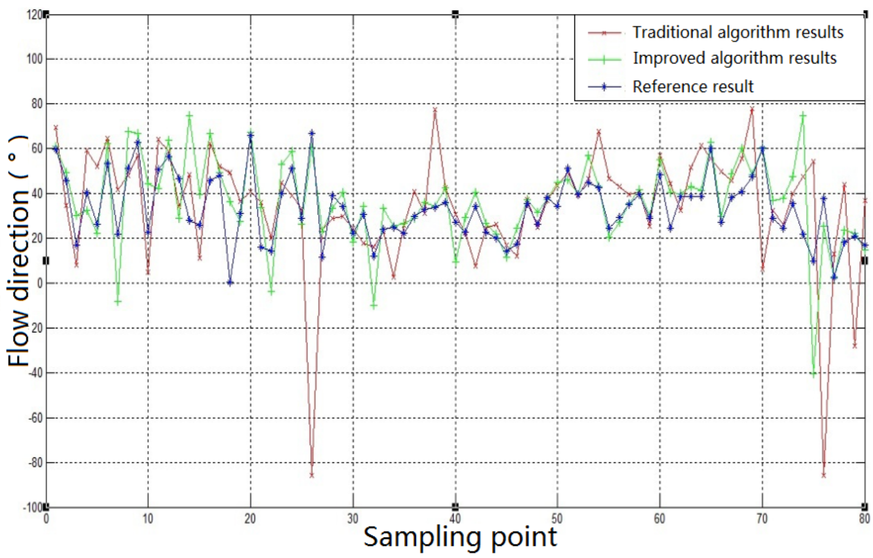

FIGURE 7. Current direction contrast diagram

TABLE 1. Experimental results for relative positioning errors

		Average error	Standard deviation
Current velocity (m/s)	Traditional Method	0.38	0.53
	Improved Method	0.17	0.41
Current direction (°)	Traditional Method	3.47	28.16
	Improved Method	2.15	18.51

5. **Conclusion.** In this paper, the new algorithms for current retrieval from X-band marine radar images were proposed and tested using radar data collected on the Haitan Island. We focus on the problem of separating waves and noise from sea surface layer inversion based on X-band radar. However, the conventional dispersion relationships band-pass filters need to measure the information of ocean current. Then, according to the characteristics of wave signal, we can build a new dispersion model to filter noise. The main idea is to fix arbitrary point wave number in the wave number frequency

space because the energy is usually higher while the noise energy is usually lower in the wave spectrum. Therefore, we can judge whether the peak of the column vector in the images belongs to the wave energy according to the peak size of the column vector in frequency direction and the character of a single peak. Thus, we can obtain the basic dispersion relation model. Then we can calculate the initial flow velocity according to the weighted minimum multiplication and use the iterative estimation method to realize the exact inversion. The new method can obtain a reliable dispersion relation model without getting the maximum current velocity in the unknown sea area. So it can carry out the initial estimation current without knowing the current velocity information. The improved algorithm proposed in this paper is applied to the X-band radar sea clutter image. According to the comparison between traditional method and WAVEX system inversion results, we can know that the proposed method is feasible and scientific.

A few of limitations should be noted. Firstly, the movement of the radar itself is not considered in this paper and it needs to be deeply discussed. Secondly, since the experimental data are limited, the inversion results under different radar polarization conditions have not been analyzed. Finally, in the algorithm verification, due to the objective conditions it is not possible to use the measured ocean current data as the reference data for comparison.

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