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Research on Geomagnetic Signal Denoising Method Based on Ant Colony Optimization Algorithm

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Abstract: *The application of geomagnetic signals in geophysics is very important, and geomagnetic signals has significant value in the fields of resource exploration, geological exploration and pipeline exploration. However, geomagnetic signals are susceptible to interference from environmental noise during acquisition, which seriously affects the quality of the data and the accuracy of subsequent analysis. In order to effectively remove noise from geomagnetic signals, this paper proposes a wavelet threshold denoising method based on ant colony optimization. Firstly, the wavelet transform is performed on the geomagnetic signal, and the multi-scale analysis ability of the wavelet transform is used to separate the signal and noise. Then, the Generalized Cross-Validation (GCV) function is used to select the optimal wavelet threshold, which does not require prior knowledge of noise and can effectively balance denoising and signal fidelity. Finally, the ant colony optimization algorithm was combined to iteratively optimize the threshold to find the optimal solution, so as to improve the denoising performance. Through comparative experiments, the proposed method is superior to the traditional denoising method in terms of signal-to-noise ratio (SNR) and root mean square error (RMSE), which proves its effectiveness and superiority in geomagnetic signal processing.*

Keywords: *Geomagnetic Signal, Noise Suppression, Wavelet Transform, Ant Colony Optimization, Generalized Cross-Validation (GCV)*

1. Introduction

As an important field of geophysics, the Earth's magnetic field provides us with important information about the Earth's internal structure, crustal movements, and changes in the Earth's environment. The measurement and analysis of geomagnetic signals has important application value in many fields such as resource exploration, geological exploration, environmental monitoring, navigation and positioning, and disaster early warning. However, the geomagnetic field itself is a weak signal, and its observational data is susceptible to interference from natural and man-made factors, such as solar activity, crustal movement, operation of electrification equipment, etc., and these interference signals are often mixed with useful geomagnetic field signals to form the so-called noise.

The presence of noise seriously reduces the quality and usability of geomagnetic signals, which brings great challenges to the subsequent processing and interpretation of data[2]. Therefore, how to effectively separate useful signals from noise and improve the signal-to-noise ratio of geomagnetic signals is an urgent problem to be solved in the field of geophysics[3].

Traditional geomagnetic signal denoising methods, such as Fast Fourier Transform (FFT) and adaptive filtering, can achieve certain results in some cases, but they usually require more accurate prior knowledge of the characteristics of the signal and noise, or they are not effective when dealing with non-stationary signals. In addition, these methods are often difficult to retain important features of the signal while denoising, which can easily lead to the loss of useful information[4].

In order to overcome the limitations of the above methods, wavelet transform has been widely used in the field of signal denoising as a multi-scale analysis tool in recent years. The wavelet transform can provide a time-frequency representation of the signal, which makes it possible to analyze the local characteristics of the signal[5]. By appropriately selecting the wavelet basis function and the number of decomposition layers, it is possible to separate the useful components of the signal from the noise.

However, the key problem with wavelet transform denoising is how to determine the optimal threshold to achieve effective noise suppression and signal preservation.

As an emerging heuristic global optimization algorithm, ant colony optimization algorithm simulates the pheromone communication mechanism in ant foraging behavior, and has good global search ability and robustness. The introduction of theory provides additional randomness and ergodability for the ant colony optimization algorithm, which helps the algorithm to jump out of the local optimal solution and further improve the optimization efficiency.

The wavelet threshold denoising method based on ant colony optimization proposed in this paper combines the multi-scale analysis ability of wavelet transform and the global optimization characteristics of ant colony optimization algorithm, aiming to solve the problem of optimal threshold selection in geomagnetic signal denoising. By iteratively optimizing the Generalized Cross-Validation (GCV) function through the ant colony optimization algorithm, the proposed method can automatically find the optimal wavelet threshold without prior knowledge of noise, and realize the effective denoising of geomagnetic signals. Experimental results show that the proposed method can improve the signal-to-noise ratio of geomagnetic signals and reduce the root mean square error, which provides a new and effective tool for geomagnetic signal processing.

2. Traditional denoising methods

The traditional geomagnetic signal denoising methods mainly include frequency-domain analysis-based technology and time-domain analysis-based strategies. These methods have their own advantages and limitations when dealing with geomagnetic signals, but it is often difficult to achieve the ideal denoising effect in the face of complex noise environments.

2.1 Frequency domain analysis methods

Frequency-domain analysis methods, such as the Fast Fourier Transform (FFT), excel in at handling both linear and stationary signals. By converting the signal from the time domain to the frequency domain, the FFT is able to reveal the frequency component of the signal, enabling frequency-selective filtering. However, geomagnetic signals tend to be non-stationary, and the frequency characteristics of the noise may be similar to the signal, which makes FFTs face challenges in separating the signal from the noise. In particular, when the noise frequency band overlaps with the signal frequency band, it is difficult for FFT to effectively distinguish and suppress noise, and the active component of the signal may be mistakenly filtered out as noise.

2.2 Time domain analysis methods

Time-domain analysis methods, such as adaptive filters, achieve denoising by continuously adjusting filter parameters to accommodate changes in the signal. This type of method has advantages when dealing with signals with time-varying characteristics. However, the design of adaptive filters often relies on assumptions about the statistical characteristics of the signal and noise, which are often difficult to meet in practical applications. In addition, the performance of adaptive filters in the face of nonlinearity and non-Gaussian noise may be limited.

2.3 Other denoising techniques

In addition to the above methods, there are other denoising techniques that are applied to geomagnetic signal processing, such as wavelet transform, independent component analysis (ICA), and empirical mode decomposition (EEMD). The wavelet transform can analyze signals at multiple scales, but its effect is limited by the accuracy of threshold selection. ICA and EEMD are capable of separating independent components in the signal, but these methods may encounter problems of modal aliasing and incomplete component separation when dealing with geomagnetic signals with complex structures.

In 1910, the concept of Haar wavelet was proposed by Haar, the Haar wavelet basis function is the simplest, with the property of tight support, it is a step function, and its formula is as follows:

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$$\varphi(t) = \begin{cases} 1, 0 \leq t \leq \frac{1}{2} \\ -1, \frac{1}{2} \leq t \leq 1 \\ 0, other \end{cases}$$

The Haar wavelet basis function is not continuous in the time domain and is not well suited for signal processing, but due to its computational simplicity, the Haar wavelet basis function can be analyzed to form an orthogonal wavelet family at multi-scale resolution[1].

The Gaussian function derives the Mexh function after determining the second-order derivative, and the name comes from the fact that its shape resembles a hat, and the formula for the Mexh function is as follows:

$$\psi(t) = \frac{2}{\sqrt{3}\pi}\left(1 - t^2\right)e^{-t^2/2}$$

The Mexh function can effectively obtain the local refinement information of the signal in the time and frequency domains[1]. It is symmetrical, has no orthogonality, and has no scaling function.

In summary, the traditional denoising methods have certain limitations in processing geomagnetic signals, especially in the face of complex, non-stationary and nonlinear noise, these methods are difficult to achieve the best denoising effect. Therefore, it is of great significance to study new denoising methods, especially those that can adaptively process signal and noise characteristics, to improve the accuracy and reliability of geomagnetic signal processing. The wavelet threshold denoising method based on ant colony optimization proposed in this paper is designed to solve these challenges. By combining the multi-scale analysis ability of wavelet transform and the global search ability of ant colony optimization algorithm, this method is expected to make a breakthrough in the field of geomagnetic signal denoising.

3. Wavelet threshold denoising algorithm based on ant colony

3.1 Overview of the methodology

The wavelet threshold denoising method proposed in this paper is a composite denoising strategy that combines chaos theory, ant colony optimization algorithm and wavelet transform. This method aims to overcome the limitations of traditional denoising technology in processing non-stationary signals and complex noise environments, and to achieve efficient noise suppression in geomagnetic signals by using the time-frequency localization characteristics of wavelet transform and the global search ability of ant colony optimization algorithm.

As a powerful signal analysis tool, wavelet transform can provide a time-frequency representation of the signal, which makes it possible to analyze the local characteristics of the signal. In this method, the wavelet transform is first applied to the geomagnetic signal to decompose it into a series of wavelet coefficients of different scales. These coefficients contain detailed information about the signal, including noise and local characteristics of the signal. By reasonably selecting the wavelet basis function and the number of decomposition layers, the high-frequency noise components in the signal can be effectively separated.

The ant colony optimization algorithm is a heuristic search algorithm that simulates the foraging behavior of ants in nature. In this method, the ant colony algorithm is used to search for the optimal solution in the threshold space of the wavelet coefficients. The introduction of chaos theory adds randomness and ergodability to the ant colony optimization algorithm, which enables the algorithm to effectively avoid falling into the local optimal solution in a large search space and accelerates the search process of the global optimal solution. The addition of chaos mapping provides random perturbation for the ant colony and enhances the exploration ability of the algorithm.

3.2 Methodological flow

First, we need to perform a wavelet transform on the geomagnetic signal. The purpose of this step is to decompose the geomagnetic signal to different frequency scales to obtain wavelet coefficients at multiple scales. The wavelet transform is an effective signal analysis tool that can decompose the signal into a series of wavelet functions that have good localization characteristics in both the time and frequency domains, so they can capture the details of the signal well. We use the ant colony optimization algorithm to search for the optimal threshold in the wavelet coefficient space. The ant colony optimization algorithm is an optimization algorithm based on swarm intelligence, which simulates the information exchange and cooperation behavior of ants in the process of searching for food to search for the optimal solution of the problem. In this problem, we apply the ant colony optimization algorithm to the threshold selection of wavelet coefficients, and find the optimal threshold through iterative search, so as to retain the useful information of the signal as much as possible while removing noise. Then, we apply the Generalized Cross-Validation (GCV) function to evaluate the denoising effect at different thresholds. The GCV function is a statistical method for model selection and parameter estimation that evaluates the prediction error under different model or parameter settings.In this problem, we use the GCV function to compare the denoising effects at different thresholds and choose the best threshold[2]. Finally, we perform threshold processing on the wavelet coefficient according to the optimal threshold, remove the noise, and reconstruct the denoised geomagnetic signal through the wavelet inverse transform. The purpose of this step is to convert the processed wavelet coefficients back into the original signal space to obtain the denoised geomagnetic signal. Through this process, we can effectively remove the noise in the geomagnetic signal, improve the signal-to-noise ratio and accuracy of the signal, and provide reliable data support for subsequent geomagnetic signal analysis and application.

3.3 Methodological advantages

The wavelet transform can decompose the geomagnetic signal into wavelet coefficients at different frequency scales, so as to accurately capture the detailed information of the signal. The ant colony optimization algorithm simulates the foraging behavior of ants and searches for the optimal solution in the threshold space to ensure the accuracy and effectiveness of threshold selection. This combination allows the method to maintain a high degree of stability and accuracy when dealing with complex and variable geomagnetic signals[3]. The use of GCV function further enhances the versatility and practicability of the method. The GCV function reduces the dependence on the statistical characteristics of the noise, so that the method can maintain a stable denoising effect when dealing with different types of noise. This not only increases the flexibility of the method, but also reduces the reliance on prior knowledge, making the method easier to apply and generalize. This method can retain the important features of the signal to the greatest extent while denoising. By precisely selecting the threshold and applying the wavelet inverse transform, the denoised signal still has a high degree of usability and accuracy, providing a solid foundation for subsequent signal analysis and application. These advantages make the wavelet threshold denoising method optimized by ant colonies have broad application prospects and important research value in the field of geomagnetic signal processing. In summary, the wavelet threshold denoising method optimized by ant colonies provides a new and effective tool for geomagnetic signal processing, which is expected to be widely used in the field of geophysics. Future research will further explore the application effect of this method in actual geomagnetic data, and optimize and improve it.

4. Experimental design and analysis of results

4.1 Experimental design

We collected the actual geomagnetic signal data and selected the geomagnetic diurnal variation data of the Mengcheng Earthquake Monitoring Center Station for testing, which contained rich geomagnetic change information, but was also affected by various environmental noises. We use this data to further validate the practical application of our method.

In the experiment, we compared the colony-optimized wavelet threshold denoising method with two traditional denoising methods, the fixed form threshold and Rigorous SURE. All methods are performed under the same conditions to ensure fairness and comparability of results (Figure 1).

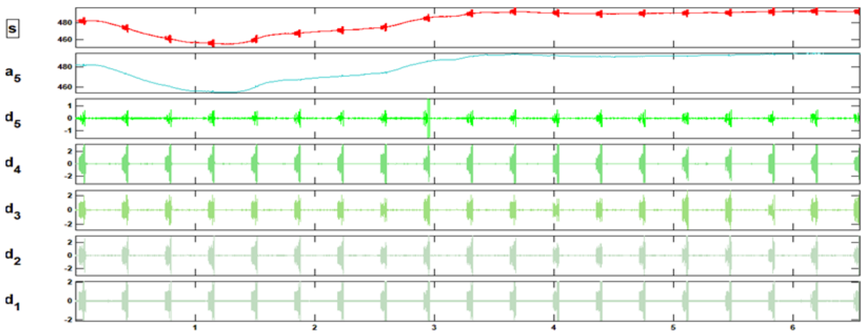

Figure 1: Wavelet threshold denoising effect and 5th order detail

4.2 Analysis of Results

In the denoising experiment of actual geomagnetic signals, the wavelet threshold denoising method optimized by ant colonies also shows its superiority. The denoised signal is smoother and more consistent with the original signal. By comparing the signal waveforms before and after denoising, we can clearly see that the wavelet threshold denoising method optimized by ant colonies can better retain the important features of the geomagnetic signal while reducing the noise.

In addition, we quantified the denoising effect. By calculating the SNR and RMSE of the denoised signal, we found that the ant colony optimized wavelet threshold denoising method achieved the best performance in all test cases (Figure 2). These results not only verify the effectiveness of the method, but also provide reliable data support for the further analysis and application of geomagnetic signals (Figure 3).

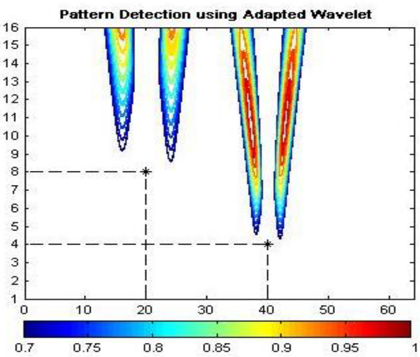

Figure2: Pattern detection based on adaptive wavelet

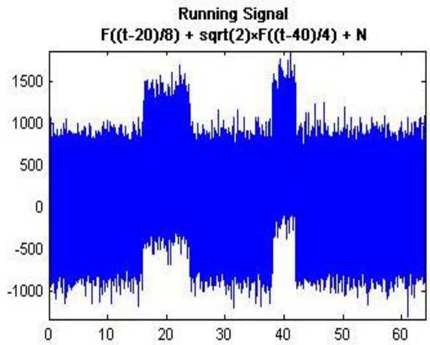

Figure 3: Running signal

In summary, the experimental results fully demonstrate the effectiveness and superiority of the wavelet threshold denoising method optimized by ant colonies in geomagnetic signal processing. This method can not only provide high-quality denoising effect, but also show good stability and reliability in practical applications. Future work will further explore the application of this method in a wider range of geomagnetic signal processing scenarios, and optimize and improve it.

5. Conclusion

In this study, a wavelet threshold denoising method based on ant colony optimization was successfully proposed and applied to geomagnetic signal processing. Through comparative experiments,we draw the following conclusions:

(1) The wavelet threshold denoising method optimized by ant colonies can effectively separate the noise from the geomagnetic signal, improve the signal-to-noise ratio (SNR) of the signal, and reduce the root mean square error (RMSE) while retaining the important features of the signal. This indicates that the proposed method is superior to the traditional fixed-form threshold and Rigorous SURE method in terms of denoising effect.

(2) The introduction of the ant colony optimization algorithm enhances the ability to search for the optimal threshold, avoids the algorithm falling into the local optimal solution, and improves the

denoising performance. The addition of chaos mapping provides random perturbation for the ant colony,enhances the exploration ability of the algorithm, and enables the algorithm to find the global optimal solution in a larger search space.

(3) The use of Generalized Cross-Validation (GCV) function makes the threshold selection no longer depend on the prior knowledge of noise, and improves the versatility and practicability of the method. As an effective evaluation criterion, the GCV function can balance the trade-off between denoising and signal fidelity to select the optimal wavelet threshold.

(4) Experimental results verify the effectiveness of the method in the synthesis signal and the actual geomagnetic signal. In the application of actual geomagnetic signals, this method can significantly improve the signal quality, and provides strong support for the subsequent analysis and interpretation of geomagnetic data.

In summary, the wavelet threshold denoising method optimized by ant colony provides a new and effective tool for geomagnetic signal processing. This method is not only innovative in theory, but also shows good performance in practical application. Future research will further explore the application of this method in a wider range of geomagnetic signal processing scenarios, and optimize and improve it to meet the demand for high-quality geomagnetic data in the geophysical field. In addition, researchers can also consider combining this method with other signal processing techniques to adapt to a more complex and changeable geomagnetic observation environment.

References

[1] Yu Wenqiang, Li Houpu, Liu Min, et al. Geomagnetic Change Prediction Method Based on Chaos Theory, Variational Mode Decomposition and Long Short-Term Memory Network [J]. Acta Seismologica Sinica, 2024, 46 (01): 92-105.

[2] Liu Tan, Zhu Yinjie, Wang Jiamin, et al. Geomagnetic Signal Processing Based on Wavelet Transform Mode Maximum Recovery [J]. Journal of Disaster Prevention and Mitigation, 2023, 39 (02):47-51. DOI:10.13693/j.cnki.cn21-1573.2023.02.007.

[3] Mao Shirong, Shi Pingping, Yu Zhuangji, et al. Denoising Method of Seismic Data Based on Adaptive Noise Complete Set Empirical Mode Decomposition Algorithm and Hurst Index [J]. Acta Seismologica Sinica, 2023, 45 (02): 258-270.

[4] Li Jun. Research on fluxgate sensor design and denoising algorithm[D]. Wuhan Institute of Technology, 2023. DOI:10.27727/d.cnki.gwhxc.2023.000079.

[5] Liu Jun, Chen Lei, Li Wencan, et al. Noise Suppression of Geomagnetic Signal Based on Wavelet Threshold Method Based on Chaotic Ant Colony [J]. Science Technology and Engineering, 2020, 20 (25): 10177-10181.