Long-Wave Signal Detection Method Based on Limit Threshold Chaotic Oscillator

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Abstract. The transmission of long-wave signal in lightning is easily weakened to a very low amplitude, and affected by non-stationary time-varying strong noise, which makes the detection signal become extremely difficult, and it is difficult to achieve the extraction of useful information. As the main noise source of interference long wave signal, this paper studies the chaos detection method of lightning noise, proposes the detection method of long wave signal based on the limit threshold chaotic oscillator, combines the Euler equation, the main frequency ratio phase change discrimination algorithm and other technologies, based on the non-linear signal processing technology, completes the chaos detection of long wave weak signal by simulating the noise environment in the laboratory, its reliability is verified by theoretical experiments, which can provide an important basis for the development of long-wave reception technology.

1. Introduction

In recent years, long-wave signal has been widely used in navigation station, marker station, long wave time service station, seismic monitoring station and other departments because of its advantages such as long propagation distance, strong diffraction ability and little ionosphere influence. In addition, long wave is easy to penetrate the sea water, which is convenient for marine exploration research. However, due to the influence of lightning noise in bad atmospheric environment, when the long wave signal reaches the detection end, it presents the problems of weak signal and low signal-to-noise ratio, which makes the signal transmission not smooth or even interrupted.

The traditional method to deal with atmospheric lightning noise is the limiting method[1]. This method was widely used in the 1970s. However, due to the lack of new theory and new technology breakthrough, the method structure has not been greatly updated and changed in recent decades. Although this method can eliminate most of the pulse components in the lightning noise, it can also eliminate the part of the useful signal interfered by the pulse noise. When the proportion of the pulse components in the lightning noise is small, the detection performance of the communication system can be improved to some extent. But when the noise is strong, the denoising effect is poor.

Therefore, this paper focuses on the exploration of new lightning noise processing methods, applies chaos theory to the detection of long wave weak signal, and realizes the detection of long wave weak signal in the background of atmospheric lightning noise.

2. Analysis and modeling of atmospheric lightning noise characteristics

In order to detect the long wave signal based on chaotic oscillator, it is necessary to study the statistical characteristics of atmospheric noise.
2.1. Statistical characteristics analysis of atmospheric lightning noise

The atmospheric noise in the long wave band is mainly caused by lightning instantaneous discharge[2,3], which is in the form of strong impulse noise. The lightning impulse noise is mainly formed by the superposition of lightning electromagnetic pulse near the detector. The pulse energy is very strong and the duration is very short. The noise energy is mainly concentrated in the pulse component.

The analysis shows that the atmospheric noise is the sum of background noise and impulse noise:

\[ n(t) = v(t) + w(t) \]  

(1)

\( n(t) \) is the total atmospheric noise, which can be regarded as the sum of two independent random processes: \( w(t) \) is background noise. Generally speaking, background noise is a Gaussian random process which is composed of a large number of thunderstorms in the world and tends to mean zero and variance \( \sigma_0^2 \). \( v(t) \) is the pulse part, which can be regarded as the sum of numerous narrow pulses generated randomly, expressed by unit impulse function:

\[ v(t) = \sum_{m=1}^{\infty} a_m \delta(t - \tau_m) \]  

(2)

Where, \( a_m \) is the random amplitude of the pulse, \( \tau_m \) is the random delay, and \( a_m \) is a random sequence, independent of the noise \( n(t) \).

2.2. Establishment of lightning noise model in atmosphere

In order to study the detection of long wave weak signal based on chaotic oscillator, the front noise of the detector must be modelled. Therefore, a noise model is needed to describe the characteristics of atmospheric lightning noise reasonably, and it is suitable for the simulation calculation of long wave signal transmission system.

For the long wave weak signal, the detector bandwidth is sufficiently small compared with the central frequency of the frequency band, generally about \( 10^{-2} \) of the central frequency, which makes the detected atmospheric lightning noise can be assumed as a narrow-band random process. In the actual system, this assumption can almost always be satisfied, and it is far from Gauss assumption, so the noise modelling problem can be simplified.

According to the measurement data of lightning noise, it is pointed out that this kind of noise has the Gaussian characteristic in the low amplitude part and the envelope of approximate exponential normal distribution in the high amplitude part. Because the high amplitude has a great influence on the performance of any communication system, the model focuses on the exponential normal characteristics of atmospheric lightning noise. The atmospheric lightning noise is simulated as a narrow-band process with exponential normal envelope in the following form:

\[ a(t) = Ae^{\alpha t} \sin[w_0 t + \vartheta(t)] \]  

(3)

In the formula, \( n(t) \) is a real stationary Gaussian random process with mean value of 0 and variance of \( \sigma_n^2 \). \( A \) is a constant (determined by noise power estimation) and a random phase process \( \vartheta(t) \), which is independent of Gaussian process \( n(t) \). The measurement results of the instantaneous frequency distribution of atmospheric lightning noise show that the frequency distribution is similar to that of narrowband Gaussian noise \( \vartheta(t) \), that is to say, even though the envelope distribution of atmospheric lightning noise is quite different from that of Gaussian noise at large envelope value, their phase and frequency parts are similar. Therefore, \( \vartheta(t) \) is assumed that the phase characteristic is similar to that of narrow-band Gaussian process. This means that at any given time \( t_0 \), the phase \( \vartheta(t_0) \) is a random variable uniformly distributed on \([0, 2\pi]\), and it is independent of the envelope.

The exponential normal narrow band noise model of atmospheric lightning noise is given by
equation (4). The noise envelope is:

\[ E(t) = Ae^{n(t)} \]  

(4)

Considering the average voltage and root mean square (RMS) voltage of the envelope, the average voltage is:

\[ E_{av} = \bar{E}(t) = Ae^{n(t)} = Ae^{\sigma_n^2/2} \]  

(5)

RMS voltage is:

\[ E_{rms} = \sqrt{\bar{E}^2(t) = \left[ A^2 e^{2n(t)} \right]^{1/2} = Ae^{\sigma_n^2} } \]  

(6)

The voltage deviation \( V_d \) is defined as:

\[ V_d = 20 \log_{10} \left( \frac{E_{rms}}{E_{av}} \right) = 20 \log_{10} (e^{\sigma_n^2/2}) = 10\sigma_n^2 \log_{10} e \]  

(7)

The values \( \sigma_n^2 \) given for \( V_d \) are estimated in the CCIR report. \( V_d \) is used to determine the variance \( \sigma_n^2 \) of random process \( n(t) \) in the envelope \( e^{n(t)} \) of atmospheric lightning noise. It determines the proportion of impulse components in the atmospheric lightning noise. It can be considered that different \( V_d \) values represent the atmospheric lightning noise under different weather conditions. The greater \( V_d \), the worse the weather where the detector is located, and the more severe the lightning in the atmosphere. For example, \( V_d = 2 \) can be considered as ordinary weather environment, \( V_d = 4.5 \) can be considered as slightly worse weather environment, and \( V_d = 7 \) and \( V_d = 10 \) can indicate that the detector has been in a thunderstorm environment.

3. Detection of sinusoidal weak signal in the background of lightning noise

Both theory and simulation experiments show that chaos oscillator[4] has a good ability to restrain any noise with zero mean value, no matter it is white noise or colour noise. The addition of zero mean noise will not change the original motion state of the system, but is reflected in the roughness of phase trajectory.

Consider the mean value of atmospheric lightning noise defined by equation (3):

\[ E[a(t)] = E\left[Ae^{n(t)} \sin(w_0t + \theta(t)) \right] \]  

(8)

Random process \( n(t) \) and \( \theta(t) \) are independent, so there are:

\[ E[a(t)] = E\left[Ae^{n(t)} \sin(w_0t + \theta(t)) \right] = AE\left[e^{n(t)} \right]E[\sin(w_0t + \theta(t))] \]  

(9)

Because \( \theta(t) \) of its uniform distribution \([-\pi, \pi] \):

\[ E[\sin(w_0t + \theta(t))] = \frac{1}{2\pi} \int_{-\pi}^{\pi} \sin(w_0t + \theta(t))d\theta = 0 \]  

(10)

That is to say, the mean value of lightning noise defined by the exponential normal narrow-band noise model is zero.

It can be seen from equation (10) that the mean value of atmospheric lightning noise is always zero, that is to say, chaos oscillator also has a certain inhibition effect on atmospheric lightning noise. Using chaotic oscillator to detect the long wave signal polluted by atmospheric lightning noise can give full play to the excellent anti noise performance of chaotic oscillator, which provides a theoretical basis for the reliable detection of long wave signal in the background of atmospheric lightning noise.

Set \( V_d = 2, 4.5, 7 \) and 10 respectively, simulate the atmospheric lightning noise according to the process shown in 2.2 quarter, and obtain the envelope of atmospheric lightning noise generated under different values as shown in Figure 1.
When using chaotic oscillator to detect the weak signal under the background of strong noise, the detection model is as follows [5,6]:

\[ \ddot{x}(t) + k \dot{x}(t) - x(t) + x^3(t) = \lambda \cos(\omega t) + a \cos(\omega t) + \eta(t) \] (11)

Among them, \( a \cos(\omega t) \) is the signal to be measured, \( \eta(t) \) is the random noise voltage deviation, the parameters are set as follows: system damping ratio \( k = 0.5 \), initial value is set as \((x, \dot{x}) = (0, 0)\).

3.1. A method of setting chaos threshold based on perturbation frequency ratio criterion

The determination of threshold value of chaos detection is one of the most critical factors to determine the detection performance. To solve this problem, this paper proposes a method to determine the threshold value based on the frequency ratio of perturbation solution. The new threshold determination method can accurately distinguish the fractal state and improve the reliability of subsequent signal detection. First of all, the first-order perturbation equilibrium solution of chaotic oscillator is the main factor affecting the main frequency component. On this basis, the empirical mode decomposition method is used to selectively reconstruct the effective parameter information, and the ratio coefficient under the minimum mean square error constraint is used to redefine the system state. The mapping relationship between the frequency ratio of the system and the amplitude of the policy force is obtained, which is the basis for determining the threshold value. Algorithm target: To obtain the threshold value \( \lambda_0 \) to be used for signal detection within \( \lambda \in H \). The algorithm flow is as follows:

**Table 1.** Determination steps of limit threshold based on frequency ratio

| INPUT: \((H, \Delta\lambda)\) | OUTPUT: \((R_m) \Rightarrow \lambda_0\). |
|-----------------------------|----------------------------------|
| 1 Determine the periodic solution: \(x_0 = g(H_i)\), | First order perturbation solution: \(x_i = f(H_i)\). |
| 2 Output first order approximate solution of the system: \(x = \sum x_i, i=0, 1\). | |

![Figure 1.](image-url)
3 Pre-treatment of relevant parameters:

\[ x(t) = \sum_{i=1}^{k} \text{imf}_i(t) + r_n(t). \]

4 Signal reconstruction: \( \hat{s}(t) = \sum_{i=0}^{k} \text{imf}_i = \hat{m}_i, i \in I \).

5 \( Y(\omega) = \text{FFT}(\hat{s}). \)

6 \( \text{sort}[Y(\omega)] \), get the main frequency intensity: \( P(\omega_0) = Y^2(\omega_0), \ P(\omega_i) = Y^2(\omega_i). \)

7 Filter norm: \( D \leq \| \omega_0 - \omega_i \|. \)

8 Determine the frequency ratio: \( R_n = \frac{P(\omega_0)}{P(\omega_i)}. \)

9 Reset system parameters \( H(\lambda), \) solve \( R_n \).

10 Get the limit threshold \( R_n \rightarrow 0 \Rightarrow \lambda_0. \)

Adjust the built-in cycle power intensity of the system to the threshold value in Table 1, so that the system is in a critical state, as shown in Figure 2.

(a) The phase diagram of Duffing oscillator  (b) The instantaneous frequency

**Figure 2.** The Phase diagram and instantaneous frequency in chaotic critical motion

Set \( V_d \) to 2, 4.5, 7, and 10, respectively. The intensity of the signal to be measured is \( B=0.02V \) and then the sinusoidal signal polluted by different intensity of atmospheric lightning noise is added. The intensity of the atmospheric lightning noise is mainly determined by the amplitude envelope value \( A \). The detection of the signal to be measured under the background of different intensity of atmospheric lightning noise is realized by the phase transition of the system[7,8]. The anti noise based on chaos detection algorithm of chaos oscillator in different atmospheric environment is studied. The simulation results of performance and SNR threshold are as follows.
When the noise $V_d$ is small ($V_d = 2$), it mainly shows Gauss characteristics, and $A = 0.31$ is regulated. The signal to be measured polluted by lightning noise in the atmosphere is shown in Figure 3 (a). The sine signal to be measured is completely submerged in the noise. The noise signal to be measured is added to the chaos detection system, and the system quickly changes to a large-scale periodic state. The phase diagram of the system output is shown in Figure 3 (b), and the signal-to-noise ratio of the signal to be measured is -30.1422 dB.

When $V_d$ is large ($V_d = 4.5$), the pulse component in the noise will continue to increase and adjust $A = 0.06$. The signal to be measured polluted by the atmospheric lightning noise is shown in Figure 4 (a). When the signal to be measured with noise is added, the system will rapidly change to a large-scale periodic state with phase transition, and the phase diagram of the system output is shown in Figure 4 (b). At this time, the signal detection threshold of the system is -25.4367db.

![Figure 3. The state of chaotic oscillator (V_d = 2)](image1)

![Figure 4. The state of chaotic oscillator (V_d = 4.5)](image2)

The simulation results show that the long wave signal detection method based on the limit threshold chaotic oscillator proposed in this paper has strong immunity to the atmospheric lightning noise, and can be applied to the detection of long wave weak signal in the background of atmospheric lightning noise. The algorithm in this paper has a very strong ability to suppress any noise with unknown distribution of zero mean and a lower SNR working limit, which is incomparable with other existing signal processing methods.

4. Summary
It is an important problem to enhance the ability of weak signal detection under the condition of strong noise. In this paper, the calculation method of chaotic limit threshold is given, a long wave signal detection method based on limit threshold chaotic oscillator is proposed, and the statistical characteristics of atmospheric lightning noise are studied and modeled, and the detection performance of this method in the environment of atmospheric lightning noise is analyzed through simulation. The experimental results confirm that the algorithm in this paper is effective in the background of complex atmospheric sky electric noise. The reliability of detection has a certain guiding significance for improving the performance of existing long wave signal detection.

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