

Postprint: Asymmetry Analysis of Rieger-type Periods in Solar Northern and Southern Hemispheres Based on CEEMD-SSWT

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Date: 2024-12-03T00:00:00+00:00

Abstract

CEEMD (Complete Ensemble Empirical Mode Decomposition) is an adaptive filtering algorithm proposed in recent years, while SSWT (Synchrosqueezed Wavelet Transform) is a current high-resolution time-frequency analysis algorithm. By employing CEEMD for pre-filtering processing of daily sunspot area data and subsequently utilizing SSWT to analyze the Rieger-type periodic asymmetry between the solar northern and southern hemispheres, more precise extraction of solar periodic signals is achieved. The research results indicate: (1) Although the activity intensity of the entire northern hemisphere is higher than that of the southern hemisphere, the average periodic scale of the Rieger-type periodic signals across the 13 solar cycles is extremely similar; (2) The solar activity intensity between the northern and southern hemispheres is significantly asymmetric, but in most solar cycles, the solar activity maximum also represents the period when the asymmetry of solar activity between the two hemispheres is weakest; (3) There is no significant correlation between the intensity of solar activity and the average period of solar Rieger-type periodic signals; it is not the case that in every solar cycle, the hemisphere with higher solar activity intensity necessarily has a smaller average period of the corresponding hemispheric Rieger-type periodic signal, nor that the hemisphere with lower activity intensity necessarily has a larger average period; (4) Rieger-type periods typically appear near the solar activity maximum, but in some solar cycles, the Rieger-type period exhibits multiple fluctuations and can also appear during the rising or declining phases of solar activity.

Full Text

Asymmetry Analysis of Solar Northern and Southern Hemisphere Rieger-type Period Based on CEEMD-SSWT

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ABSTRACT

CEEMD (Complete Ensemble Empirical Mode Decomposition) is an adaptive filtering algorithm proposed in recent years, and SSWT (Synchrosqueezed Wavelet Transform) is a current high-resolution time-frequency analysis algorithm. In this paper, CEEMD is used to pre-filter the sunspot daily area data, and then SSWT is used to analyze the Rieger-type period asymmetry of the northern and southern hemispheres to achieve a more accurate extraction of the solar period signal. The results show that: (1) although the intensity of activity is higher in the Northern Hemisphere than in the Southern Hemisphere as a whole, the mean period scales of the Rieger-type period signal for the entire 13 active cycles of the two hemispheres are extremely similar; (2) there is a clear asymmetry in the intensity of solar activity between the northern and southern hemispheres, but during most of the active weeks, the period of maximum solar activity is also the period of weakest asymmetry between the northern and southern hemispheres; (3) there is no clear correlation between the intensity of solar activity and the mean period of the solar Rieger-type period signal, and it does not follow that the higher the intensity of activity, the smaller the mean period of the Rieger-type period signal in the corresponding hemisphere, and the lower the intensity of activity, the larger the mean period of the Rieger-type period signal in the corresponding hemisphere; (4) the Rieger-type period usually occurs near the maximum period of solar activity, but in some cycles the Rieger-type period shows multiple fluctuations and can also occur during periods of rising or falling solar activity.

Key words Sun: activity, Sun: spots, technology: CEEMD-SSWT

Solar activity is closely related to the Earth, exerting strong influences on Earth's magnetic field and atmosphere, making research on solar characteristics particularly necessary. Among these, the asymmetry of solar activity between the northern and southern hemispheres is a fundamental feature of the astrophysical dynamo [1]. The Rieger-type period is a well-known solar activity cycle discovered in gamma-ray flares [2], with a duration of approximately 150–180 days [2,3]. It shares similar characteristics with solar north-south hemisphere activity, including hemispheric asymmetry [4]. Traditional methods for studying the asymmetry of the Rieger-type period between hemispheres typically involve wavelet analysis [5] and the LSP (Lomb-Scargle Periodogram) method [6] to

extract periodic features [7]. While wavelet analysis can effectively extract features from complex multi-frequency astronomical signals, when extracting the Rieger-type period, it may result in cases where the Rieger-type period appears absent in certain solar cycles during local analysis, possibly due to the combined influence of relatively weak toroidal magnetic fields and torsional oscillations [8].

Intelligent signal processing algorithms offer advantages over wavelet analysis for feature extraction in that they can adapt to various signal types, including periodic and non-periodic signals. For signals with rapid or unstable period changes, intelligent algorithms can effectively extract periodic signals from solar cycle activity [9]. Although both EMD (Empirical Mode Decomposition) and CWT (Continuous Wavelet Transform), commonly used for extracting narrowband periodic signals, have obvious limitations, SSWT can more accurately extract instantaneous frequency and amplitude information of signals by reassigning wavelet coefficients, thus providing better performance in signal reconstruction. In contrast, EMD is prone to mode mixing, and CWT may suffer from inaccurate signal reconstruction or information loss [10]. Therefore, this paper utilizes the concept of morphological component analysis by combining the characteristics of CEEMD (Complete Ensemble Empirical Mode Decomposition) and SSWT (Synchrosqueezed Wavelet Transform). First, CEEMD is used to decompose the signal into modes, then SSWT is used to reconstruct signals in specific frequency intervals to extract the Rieger-type signal. Subsequently, an asymmetry analysis is conducted on the intensity of solar activity in the northern and southern hemispheres and the mean period scale of the Rieger-type signal across cycles 12–24.

2.1 CEEMD-SSWT Algorithm

CEEMD, as an optimized algorithm of EMD [11], possesses stronger anti-aliasing and anti-noise capabilities than EMD [12]. Such adaptive filtering algorithms solve problems like the difficulty of basis function selection in CWT [13]. The concept is to decompose a multi-frequency signal into multiple single-frequency IMFs (Intrinsic Mode Functions):

$$x(n) = \sum_{m=1}^k c_m(n) + r_k(n)$$

where $x(n)$ ($n = 1, 2, \dots, N$) is the original input signal, k is the number of IMFs decomposed, $c_m(n)$ ($m = 1, 2, \dots, k$) are the corresponding modes, and $r_k(n)$ is the residual signal.

First, positive and negative signals are obtained by adding positive and negative Gaussian white noise to $x(n)$:

$$\begin{aligned} x_p(n) &= x(n) + e_q(n) \\ x_q(n) &= x(n) - e_q(n) \end{aligned}$$

Then, the positive and negative signals are processed multiple times to obtain sequences containing IMF components. The final CEEMD decomposition result is:

$$c_m(n) = \frac{c_{pm}(n) + c_{qm}(n)}{2}$$

$$r_k(n) = \frac{r_{pk}(n) + r_{qk}(n)}{2}$$

where $c_m(n)$ is the final IMF component of the original input signal $x(n)$, $r_k(n)$ is the residual signal, $c_{pm}(n)$ and $c_{qm}(n)$ represent the final positive and negative mode signals after processing, and $r_{pk}(n)$ and $r_{qk}(n)$ represent the final positive and negative residual signals after processing.

SSWT, as a high-resolution time-frequency analysis algorithm, inherits CWT theory. For a signal (including noise) $y(t)$, its wavelet coefficients are expressed as:

$$W_y(a, b) = a^{-1/2} \int_{-\infty}^{\infty} y(t) \psi^* \left(\frac{t-b}{a} \right) dt$$

where $W_y(a, b)$ is the corresponding wavelet coefficient of signal $y(t)$ at scale a ($a \in \mathbb{R}^+$) and translation (time shift) value b ($b \in \mathbb{R}$), $\psi(t)$ is an appropriate mother wavelet, and $\psi^*(t)$ represents the complex conjugate of $\psi(t)$.

The instantaneous frequency $\omega_y(a, b)$ of signal $y(t)$ is expressed as:

$$\omega_y(a, b) = -i \frac{\partial W_y(a, b) / \partial b}{W_y(a, b)}$$

where i is the imaginary unit. By transferring information from the time-scale plane to the time-frequency plane, the frequency variable ω and scale variable a are merged [14].

The signal in a frequency range of the continuous frequency domain is then compressed into a point in the discrete frequency domain. Typically, in the synchrosqueezing operation, $W_y(a_z, b)$ is calculated from signal $y(t)$ at the z -th discrete scale value a_z , which is the wavelet coefficient corresponding to this discrete scale value, with instantaneous frequency ω_l :

$$T_y(\omega_l, b) = (\Delta\omega)^{-1} \sum_{a_z: |\omega_y(a_z, b) - \omega_l| \leq \Delta\omega/2} W_y(a_z, b) a_z^{-3/2} \Delta a_z$$

where $T_y(\omega_l, b)$ represents the energy value corresponding to the discrete angular frequency ω_l obtained by squeezing in the continuous interval $[\omega_l - \Delta\omega/2, \omega_l + \Delta\omega/2]$, $\Delta a_z = a_z - a_{z-1}$, $\Delta\omega = \omega_l - \omega_{l-1}$.

Finally, through inverse CWT operation, the original signal $y(t)$ can be obtained as follows:

$$y(t) = \text{Re} \left[C_\psi^{-1} \int_0^\infty \left(\int_{-\infty}^{\infty} T_y(\omega, t) d\omega \right) \frac{\hat{\psi}^*(\omega)}{a} \frac{da}{a} \right]$$

where Re represents the real part, a is the scale variable, ω is the frequency domain symbol, $\hat{\psi}$ is the Fourier transform of the mother wavelet $\psi(t)$, and C_ψ is the normalization constant [15].

2.2 CEEMD-SSWT Algorithm Flow

MCA (Morphological Component Analysis) primarily utilizes differences between different signal components to separate signals. Since signals are linear

combinations of multiple components with different morphologies, each component can find a dictionary that provides a sparse representation for that component but not for others. This intra-class sparsity and inter-class incoherence pattern representation is similar to the concept of adaptive filtering algorithms.

[Figure 1: see original paper] shows the flowchart of the CEEMD-SSWT algorithm for extracting the Rieger-type average period. The algorithm interpolates the raw daily sunspot area data for both hemispheres, then performs modal decomposition using CEEMD. The Fourier spectrum is used to select the spectrum corresponding to the Rieger-type period signal, removing useless signals such as noise in the sunspot data and spectral modes where non-Rieger-type signals reside. SSWT then performs frequency band screening again on the obtained useful signals. In these two steps, both algorithms achieve the purpose of removing signal noise while performing modal decomposition and frequency screening [16,17]. Since the accuracy of SSWT signal screening and reconstruction is related to the complexity of the original data, this paper first uses CEEMD to screen out usable signals to reduce the difficulty of SSWT data processing, and finally reconstructs the Rieger-type signal through SSWT.

3.1 Simulated Signal Testing

To verify the advantages of combining CEEMD-SSWT through MCA concepts over directly using SSWT to extract specific frequency band signals, we constructed simulated signal tests to compare the reconstruction capabilities of both methods. First, we built composite signal 1 by constructing cosine signals with frequencies of 12, 14, 16, 18, and 27 Hz, plus a high-frequency cosine signal of 1000 Hz, and finally adding Gaussian white noise with a signal-to-noise ratio of 3, as shown in Figure 2: see original paper. Then, all sine signals in the composite signal were added to obtain composite signal 2, as shown in Figure 2: see original paper. The known composite signal 2 is used to test the fixed frequency band screening and reconstruction capabilities of SSWT and CEEMD-SSWT. Using composite signal 2 as the known test signal, both methods process composite signal 1. By comparing the residuals between the extracted signals and the original composite signal 2, we can determine which method can more accurately reconstruct the test signal.

The extraction of test signals by both methods is shown in [Figure 3: see original paper]. These are the residual comparison results after processing composite signal 1 and extracting the test signals using SSWT and CEEMD-SSWT, respectively. Figure 3: see original paper and Figure 3: see original paper clearly show that neither method can precisely reconstruct complex signals; both algorithms have smaller reconstruction errors in the middle but larger reconstruction deviations at signal edges due to algorithmic limitations. In Figure 3: see original paper, the dot-dashed line and dotted line represent the residuals of the test signal extracted by the MCA-based CEEMD-SSWT method and SSWT, respectively. The residual comparison of the two algorithms in Figure 3: see original paper shows that the reconstruction residual of CEEMD-SSWT is smaller than

that of SSWT, and the reconstruction accuracy of CEEMD-SSWT is higher than SSWT at the boxed areas in the figure.

3.2 Dataset

Sunspot area is an important indicator of solar activity, providing information about different aspects of solar activity intensity and variation. For data selection, we use daily sunspot area data from the Royal Greenwich Observatory for the period 1874–2016.

3.3 Actual Data Experiments and Results Analysis

First, data preprocessing is performed. Since early sunspot data may be missing, linear interpolation is used to interpolate missing sunspot data to prevent inaccurate results. The interpolated raw data image is shown in [Figure 4: see original paper].

The dominant hemisphere of solar activity is determined through equation (9). Daily sunspot data for each year are statistically analyzed to obtain the asymmetry of solar activity intensity for each solar cycle. The asymmetry is calculated using the following formula:

$$A = (N - S)/(N + S)$$

where A represents the north-south hemisphere asymmetry intensity, N represents the solar activity value in the Northern Hemisphere, and S represents the solar activity value in the Southern Hemisphere.

[Figure 5: see original paper] shows the asymmetry of solar hemispheric activity intensity, where the waveform represents the total annual solar activity intensity for each year of solar cycles 12–24, derived from annual sunspot area data from the Royal Greenwich Observatory for 1874–2016. The middle line indicates zero asymmetry between the hemispheres. The circular points represent the severity of annual north-south hemisphere activity intensity asymmetry; the farther from the line, the stronger the asymmetry in that year, and vice versa. This shows that in most solar cycles, the north-south asymmetry is relatively weak during the maximum phase, while stronger asymmetry is exhibited during the rising and declining phases.

Simultaneously, the dominant hemisphere is calculated using the above equation (9) with sunspot data. As shown in , statistical analysis of the sunspot data yields the dominant hemisphere for solar cycles 12–24. It can be seen that in cycles with larger A values, such as cycles 19 and 20, the annual data points in [Figure 5: see original paper] also appear farther from the horizontal line.

Furthermore, it is evident that cycles with stronger solar activity do not necessarily exhibit stronger north-south asymmetry. For example, cycles 17 and 18 have solar activity intensities far greater than early cycles, yet their north-south asymmetry is very weak. However, cycles 19 and 20 not only show strong

north-south asymmetry but also have intense solar activity within the cycles.

[Figure 6: see original paper] shows the modal signals of the Northern and Southern Hemispheres extracted by CEEMD from the raw sunspot signal, where Figure 6: see original paper is the Northern Hemisphere and Figure 6: see original paper is the Southern Hemisphere. The algorithm process involves performing CEEMD decomposition on the north-south hemisphere sunspot data for the entire cycles 12–24 to obtain various IMF signals. According to frequency from high to low, they are IMF1–IMF14 from top to bottom. Due to the complexity of sunspot data, each IMF cannot completely represent the corresponding solar cycle signal, but CEEMD has strong anti-mode-mixing and anti-noise capabilities. The spectrograms in [Figure 7: see original paper] also show that the decomposed IMFs can almost encompass all solar cycles.

[Figure 7: see original paper] shows the Fourier transform of each IMF in [Figure 6: see original paper], where Figure 7: see original paper is the Northern Hemisphere and Figure 7: see original paper is the Southern Hemisphere. From these, IMF1 and IMF2 are clearly high-frequency noise in astronomical signals. IMF7 and IMF8 have main frequency distributions between 0.004–0.01 Hz, which is actually the frequency range where the Rieger-type signal resides. In addition to IMF7 and IMF8 representing the Rieger-type period, there are other IMFs representing solar cycles, such as IMF11 representing the 11-year solar activity cycle [18,19], IMF4 representing the 27-day period caused by magnetic structure rotation due to solar rotation [20,21], and IMF8, IMF9, IMF10 representing the 1.2–3.5 year quasi-biennial oscillation (QBO) [22,23]. However, precisely because of the limitations of the CEEMD algorithm mentioned above, the modal decomposition is not thorough enough, resulting in IMF8 containing both considerable Rieger-type signal frequency bands and QBO frequency bands.

Therefore, the method of extracting solar cycle signals through modal decomposition has significant limitations. Previous literature has also studied extracting solar cycle signals from Wilson Mountain magnetic index data through synchrosqueezed transform [10]. However, modal decomposition methods always suffer from mode mixing and noise influence. To avoid mode mixing, particularly the difficulty of one modal signal representing the entire Rieger-type period signal, it is necessary to select and recombine the decomposed modes and use SSWT for frequency band screening to concentrate the extracted signal frequency more in the Rieger-type period signal band.

IMF7 and IMF8 selected from the spectrogram in [Figure 7: see original paper] are combined to extract the Rieger-type period signal, with results shown in [Figure 8: see original paper]. Figure 8: see original paper and Figure 8: see original paper are the useful signals extracted using CEEMD, while Figure 8: see original paper and Figure 8: see original paper are the Rieger-type signals obtained by SSWT frequency band screening of the useful signals from both hemispheres. The frequency band screening interval is set to 0.0034–0.008 Hz, corresponding to signals with periods of 125–300 days, to obtain the Rieger-type

period signal as shown in Figure 8: see original paper-(d). In [Figure 9: see original paper], Fourier transform is performed again on the useful signals and Rieger-type period signals for the Northern and Southern Hemispheres shown in [Figure 8: see original paper] to obtain corresponding spectrograms. It can be clearly seen that the Rieger-type signal reconstructed by SSWT has more concentrated frequency in the 125–300 day interval (corresponding to frequency 0.0034–0.08 Hz), while signals outside the frequency band are removed. In summary, the CEEMD-SSWT algorithm synthesizes modes with Rieger-type signal characteristics, highlights the Rieger-type signal, and reduces the complexity of useful signal processing, thereby improving the accuracy of Rieger-type signal reconstruction.

Next, the average period of the Rieger-type signal for the 13 solar cycles is extracted [24]. After obtaining the instantaneous frequency of the Rieger-type signal for the corresponding cycle through Hilbert transform, the probability distribution of the instantaneous frequency of the obtained Rieger-type signal is statistically analyzed. Some outliers generated due to mode mixing and Nyquist noise are removed, and Gaussian fitting is performed to obtain the average period for each cycle, as shown in [Figure 10: see original paper].

Recent studies have found that in solar cycles 19–23, the average period of the dominant hemisphere tends to be smaller [25]. is a statistical table obtained by extracting the average period of the Rieger-type signal for these 13 cycles using the above mathematical methods. In , N-AP and S-AP represent the average period of the Rieger-type signal in the Northern and Southern Hemispheres for the corresponding cycle, respectively. The average period of the Rieger-type extracted by CEEMD-SSWT does not completely coincide with results from wavelet analysis due to differences in period extraction methods. Meanwhile, because of the limitations of wavelet analysis, the average period for each solar cycle cannot be completely obtained. Additionally, due to the complexity of solar signals, the Rieger-type period information may not be prominent enough in the power spectrum, leading to inaccurate average periods or even situations where the average period appears “nonexistent.” CEEMD-SSWT can extract the Rieger-type period for each cycle through signal extraction methods, thereby obtaining the average period for each cycle.

The average period obtained from sunspot area and sunspot number fitting through CEEMD-SSWT is similar, but the data from wavelet analysis shows large differences, demonstrating the stability of intelligent algorithms in processing signal feature extraction. Meanwhile, the wavelet coefficients obtained by CWT processing of the original signal also suffer from inaccuracy issues due to CWT limitations. When highlighting the power spectrum of periodic signals, CWT limitations may cause power spectra that should be highlighted to be missed, while power spectra that should not exist in the Rieger-type signal frequency band are highlighted, ultimately leading to differences between the Rieger-type signal average period scale obtained by wavelet analysis and that obtained by CEEMD-SSWT.

In this process, SSWT processes the useful signal and reconstructs the required Rieger-type period signal. Considering the flexible scale interval of the Rieger-type period signal, the frequency reconstruction interval is set to 125–300 days, which is a large frequency interval. The frequency interval setting significantly affects the final result. The 125–300 day interval is the result of multiple experiments, which can both remove information not belonging to the Rieger-type signal to a certain extent and ensure that the final average period scale of the northern and southern hemispheres falls within the Rieger-type signal interval of 150–180 days. If the screening interval were set to only 150–180 days, some Rieger-type signals beyond this interval would not be reconstructed. However, setting the larger interval of 125–300 days largely ensures the integrity of Rieger-type signal information while also screening out many non-Rieger-type signals.

In summary, although the difference in the average period of the Rieger-type signal between the northern and southern hemispheres is not large, statistical differences exist. The average period obtained by CEEMD-SSWT shows that the magnitude of the average period is independent of solar activity intensity. Cycles with strong solar activity may have large average periods or small average periods. Meanwhile, the average period of the northern and southern hemispheres is also unrelated to the activity intensity of the hemispheres, suggesting that solar activity develops independently in the northern and southern hemispheres. This result is also observed in the QBO period [26].

Therefore, the asymmetry of activity intensity between the northern and southern hemispheres has no obvious relationship with the magnitude of the average period of their Rieger-type period signals, and there is no significant correlation with the average period scale of the Rieger-type signals in the two hemispheres.

After extracting the corresponding Rieger-type signals, the 11-year cycle signals representing solar activity are extracted from the northern and southern hemispheres. [Figure 11: see original paper] and [Figure 12: see original paper] compare the normalized extracted 11-year cycle signals and Rieger-type period signals for each hemisphere, where [Figure 11: see original paper] shows northern hemisphere sunspot data and [Figure 12: see original paper] shows southern hemisphere sunspot data. The 11-year cycle signal is IMF11 decomposed from the original solar data by CEEMD. Due to the large period interval of the 11-year cycle signal, the corresponding frequency interval required by SSWT is extremely small, making it difficult for SSWT to accurately reconstruct the 11-year cycle signal. Therefore, the 11-year cycle decomposed by CEEMD may have inaccuracies due to algorithmic limitations, such as in cycles 13 and 14 in the Southern Hemisphere.

Meanwhile, by extracting and comparing the 11-year cycle and Rieger-type period from both hemispheres, [Figure 11: see original paper] and [Figure 12: see original paper] are obtained. From the figures, it can be seen that the Rieger-type period appears near the maximum phase in most solar cycles. In the Northern Hemisphere, the Rieger-type period activity extreme points of cycles 12, 14, 15, 19, 20, 21, and 23 are near the maximum phase, and in the

Southern Hemisphere, those of cycles 12, 17, 18, 19, 20, 21, and 22 are also near the maximum phase. The Rieger-type period typically begins in the rising phase of solar activity and ends in the declining phase, intensifying as solar activity becomes more vigorous. However, in some solar cycles, the Rieger-type period shows multiple peaks, often appearing in the rising and declining phases of solar activity. For example, in cycles 13, 16, 18, and 22 in the Northern Hemisphere and cycles 15 and 20 in the Southern Hemisphere, the Rieger-type period shows multiple fluctuations. Even in Southern Hemisphere cycles 20 and 23, the Rieger-type period shows amplitude fluctuations multiple times during the rising, maximum, and declining phases of solar activity.

In summary, the Rieger-type period usually occurs near the maximum phase of solar activity, but in some cycles it shows multiple fluctuations and can also appear during the rising or declining phases of solar activity.

In this paper, we used the CEEMD-SSWT method to process daily sunspot area data from solar cycles 12–24 to more accurately extract the Rieger-type period signal from solar cycle signals. We analyzed the asymmetry of solar activity between the northern and southern hemispheres and obtained the following conclusions: (1) although the intensity of activity is higher in the Northern Hemisphere than in the Southern Hemisphere as a whole, the average period of the Rieger-type period signal across the 13 cycles is extremely similar; (2) the asymmetry between the northern and southern hemispheres is weaker during the maximum phase of most cycles and stronger during the rising or declining phases; (3) the average period of the Rieger-type signal in the northern and southern hemispheres is not strongly correlated with activity intensity—cycles or hemispheres with more intense activity do not necessarily have longer or shorter average periods for the Rieger-type signal; (4) the Rieger-type period usually appears near the maximum phase of solar activity, but in some cycles it shows multiple fluctuations and can also appear during the rising or declining phases.

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