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Transform of Lightning Electromagnetic Pulses based on Laplace Wavelet

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Abstract

In this study, the fine structures of lightning electromagnetic pulse associated with 19 preliminary breakdown pulses, 37 stepped leaders, 8 dart leaders, 73 first and 52 subsequent return strokes were analyzed by using Laplace wavelet. The main characteristics of field waveforms such as, the correlation coefficient, the time of arrival and the dominant frequency of the initial peak field, the energy and the frequency of the power spectrum peak are presented. The instantaneous initial peak field pulse can be precisely located by the value of the correlation coefficient. The dominant frequencies of the initial peak field of PB pulses and leaders range from 100kHz to 1MHz, and that of the first and subsequent return strokes below 100 and 50kHz, respectively. The statistical results show that the Laplace wavelet is an effective tool and can be used to determine time and frequency of the lightning events with greater accuracy.

Keywords: *LEMP, wavelet transform, PB pulse, leader, return stroke*

1. Introduction

Lightning is a significant cause of interruptions and damage in many pieces of electric and electronic equipments that are sensitive to the lightning electromagnetic pulse (LEMP), especially to the cloud-to-ground (CG) lightning. In order to mitigate data congestion in real time analysis and to obtain better information in lightning detection and location system, it is necessary to distinguish and analyze different lightning events with appropriate data processing algorithms.

A typical flash between cloud and ground starts in the cloud and is composed of a various discharge components. Preceded by a preliminary breakdown (PB) pulses within the cloud, a series of short luminous steps (called stepped leader) initiates the first stroke in a flash. By branching in a downward direction during its development toward ground, the stepped leaders have pulse currents, and associated with these currents are electric- and magnetic-field pulses with widths of about 1 μs or less. The first return stroke propagates up the previously ionized leader path and, in so doing, produces an electric-field change with time variations which range from submicrosecond scale to many milliseconds. The dart leader initiates a subsequent return stroke. Usually, subsequent return strokes are not branched [1].

It is important to attribute to each event in its specific characteristics, since they are able to influence the electromagnetic field radiated by those lightning events. In this study, characteristics features of LEMP have been investigated by the Laplace wavelet transform method. The advantage of this technique is that some parameters in time and frequency domain can be associated with the lightning events according to the shape of the electromagnetic field waveform. The time information could be used in lightning prediction and location calculation, and the frequency information is useful for distinction of lightning events to obtain better information about lightning flash.

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2. A Mathematical Overview of Wavelet Transform

The wavelet transform of a finite energy signal x(t), with the mother wavelet $\psi(t)$, is the inner product of x(t) with a scaled and conjugate wavelet $\psi_{a,b}(t)$, and is given by,

$$WT\ \{x(t), \psi(t)\} = \frac{1}{\sqrt{a}} \int x(t) \psi^{*}_{a,b}(t) dt \quad (1)$$

Consequently, the wavelet analysis can be viewed as an evaluation of the similarity indices between the signal and daughter wavelets ($\psi_{a,b}(t)$) located at time position b with scale a which is derived from a mother wavelet, as it is equivalent to a scalar product of the signal itself and the daughter wavelets [2]. The factor $1/\sqrt{a}$ is used to ensure energy preservation.

The Laplace wavelet transform is a complex, continuous, single-sided damped exponential wavelet which is a desirable wavelet basis to analyze signals of impulse response or transient response [3], and is defined by:

$$\psi(\omega,\zeta,\tau,t) = \psi_{\gamma}(t) = \begin{cases} Ae^{-\frac{\zeta}{\sqrt{1-\zeta^2}}\omega(t-\tau)} e^{-j\omega(t-\tau)} & (t \in [\tau, \tau + W_s]) \\ 0 & (else) \end{cases} \quad (2)$$

Where the parameter vector $\gamma = \{\omega, \zeta, \tau\}$ determines the wavelet properties and is denoted viscous damping ratio $\zeta \in [0,1) \subset R^{+}$, frequency $\omega \in R^{+}$, and time index $\tau \in R$. These parameters are related to modal dynamic properties. The damping ratio ζ controls the decay rate of the exponential envelope in the time domain; the frequency ω determines the number of significant oscillations of the wavelet in the time domain; the coefficient parameter A is an arbitrary scaling factor used for the sake of normalization, and the range W_s ensures the wavelet is the width of compact support in time domain and has nonzero finite length. Figure 1 shows the Laplace wavelet, its real part, imaginary part.

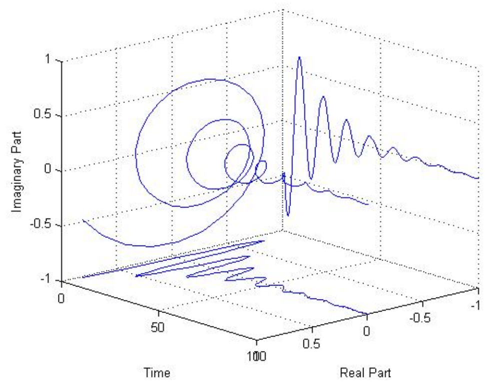

Figure 1. Real and Imaginary part of Laplace wavelet

For each wavelet, the inner product in Equation 1 results in a series of coefficients which indicate how close the signal is to that particular wavelet. To extract the time and frequency information, the correlation coefficient k_r is defined by Equation 3.

$$k_r = \sqrt{2}\frac{\left|\langle \psi_\gamma(t), x(t)\rangle\right|}{\|\psi_r\|_2\|x\|_2} \quad (3)$$

Where the normalizing factor of $\sqrt{2}$ can limit the range correlation coefficient between 0 and 1. k_r is a matrix whose dimensions are determined by the parameter vectors of $\{\omega, \zeta, \tau\}$.

For a given $\tau \in T$, the inner product operation is actually searching for a maximum correlation coefficient across the frequency ω and damping ζ. Define $k(\tau)$ as the initial peak values generated during this process and define $\bar{\omega}$ and $\bar{\zeta}$ as the parameters of the Laplace associated with peak correlation, shown as follows:

$$k(\tau) = \max_{\substack{\omega\in\Omega \\ \zeta\in Z}} k_\gamma^\tau = k_{\{\bar{\omega},\bar{\zeta},\tau\}} \quad (4)$$

The damping $\bar{\zeta}$, frequency $\bar{\omega}$, and time τ associated with peak $k(\tau)$ values indicate the modal properties of the lightning electromagnetic field which generated the waveform $x(t)$.

For a discrete sequence x_n, the wavelet power spectrum is defined as $|W_n(s)|^2$ [4].

For distinction of different lightning events, relevant parameters are extracted from the wavelet transformed contour [5, 6]. In this study, five parameters have been considered which are the initial peak fields, the dominant frequency component, the time of arrival of the initial peak field, the peak value of power spectrum, and the frequency of the power spectrum peak.

The initial peak field and the dominant frequency are determined according to the largest value of correlation coefficient $k(\tau_p)$. The parameter τ_p indicates the time of arrival of the initial peak when the lightning electromagnetic field impulse is received at receiver site. The dominant frequency component means the frequency $\bar{\omega}_p$ associated with $k(\tau_p)$, the initial peak field is the amplitude of $x(\tau_p)$, and the frequency spectra shows the frequencies $\bar{\omega}$ is related to the time during the onset of the lightning event.

The frequency of the power spectrum peak means the frequency associated with the maximum of power spectrum, and the frequency distribution means the statistics of frequencies of the power spectrum peak of these analyzed electromagnetic fields.

3. Data Acquisition

Our database is comprised of 19 preliminary breakdown pulses, 37 stepped leaders, 8 dart leaders, 73 first and 52 subsequent return strokes electromagnetic field waveforms. Most of them were recorded by the lightning detection receiver stations in Wuhan and Conghua, China, at the distance from 1 to 50km. The station includes a flat electric field antenna, two orthogonally mounted loop magnetic field antennas. This antenna system used in the acquisition data was time-synchronized with a GPS antenna, which was connected to the computer with an A/D converter and a cPCI interface. The rest of the few field waveforms have been analyzed described in [7-10].

4. Results and Discussion

For this study, the electromagnetic field waveform was convolved with the Laplace wavelet for a time-span of 20 μs for PB pulses, leaders, and 50 μs for return strokes to ensure that there is only one lightning event in the analyzed signal $x(t)$.

Temporal features of those different electromagnetic field waveforms associated with preliminary breakdown pulse, stepped leaders, and dart leaders, first and subsequent return stroke have been studied using Laplace wavelet transform computation shown in Figure 2-5. In these figures, the wavelet transform coefficient k_r , the frequency spectra, and the power spectrum $|W_n(s)|^2$ are shown.

In each figure, the first plots (a) depicts the time domain fields, and the second plots (b) depicts the corresponding wavelet transforms correlation coefficient k_r, and the third plots (c) depicts the frequency spectra in time scale, and the last plots (d) depicts the wavelet power spectra in time and frequency. The vertical axes in each plot (a) represent the field strength, whereas the vertical axes in the plots (c) represent the frequency. The horizontal axes in all plots represent the time. The wavelet power spectra are represented by colors in plots (d), and the power spectrum are represented by a color scale at the right side of the plots. A comparison among Figures 2, 3, 4, and 5 shows that, for these lightning events, the presence of the electromagnetic field initial peak can be clearly distinguished by the significant increase of the wavelet transform coefficient.

Figure 2 shows the wavelet transform of preliminary breakdown pulses (single peaked P1, P2, P4, P5, P6, P7, and multiple peaked P3). The dominant frequencies of these pulses are more than 750kHz shown in plot (c), and the frequencies of the power spectrum peak are less than 500kHz, except for P7 of about 750kHz shown in plot (d). The peak power was radiated by the multiple peaked PB pulse P3.

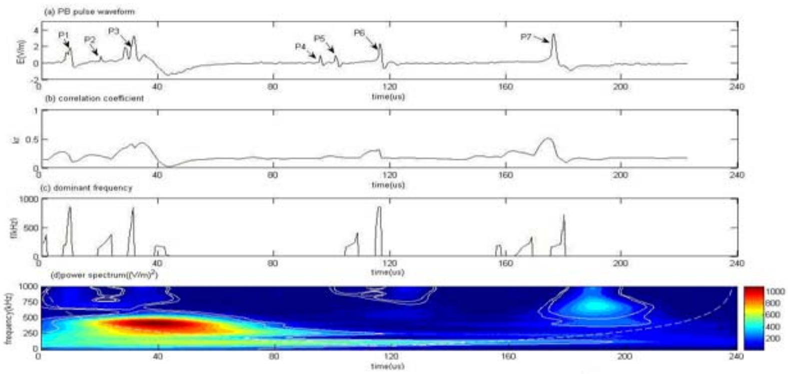

Figure 2. Wavelet Analysis of Preliminary Breakdown Pulses

Figure 3 shows the wavelet transform of stepped leaders corresponding to a negative returns stroke. The first return stroke was initiated by many VHF electromagnetic field pulses of stepped leaders. The dominant frequencies of these pulses are about 500kHz shown in plot (c), and the frequencies of the power spectrum peak are also about 500kHz shown in plot (d). The time of those stepped leader pulses can be used to predict a return stroke.

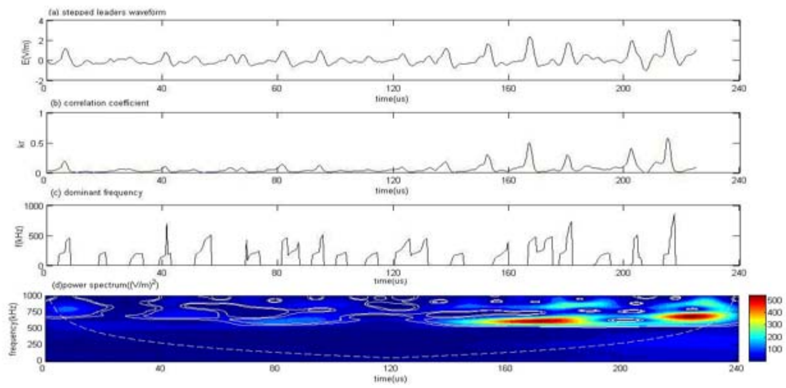

Figure 3. Wavelet Analysis of Stepped Leaders

Figure 4 and Figure 5 show the wavelet transforms of first and subsequent return strokes in a same flash. The dominant frequencies and the frequencies of power spectrum peak of return strokes are much less than the frequencies of PB pulses and leaders.

For the first return stroke, the effect of the tortuous and branching lightning channel results in a dominant frequency component of the initial peak field less than 100kHz, which is in reasonable agreement with the frequency concluded in [6], while about 20kHz for subsequent return stroke, respectively, however, which is lower than their results.

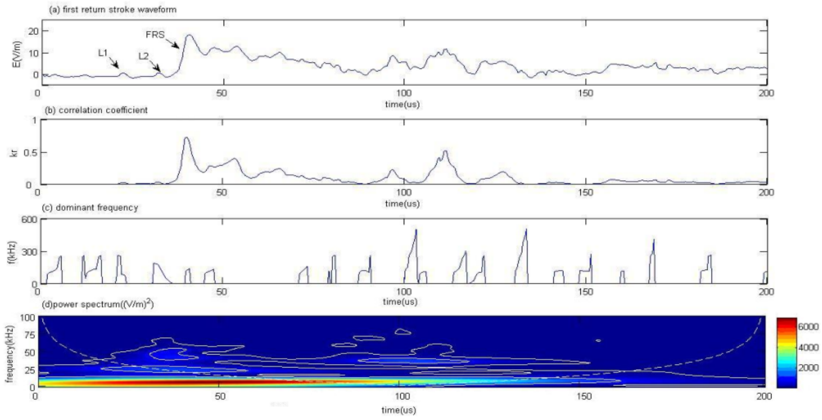

Figure 4. Wavelet Analysis of First Return Stroke

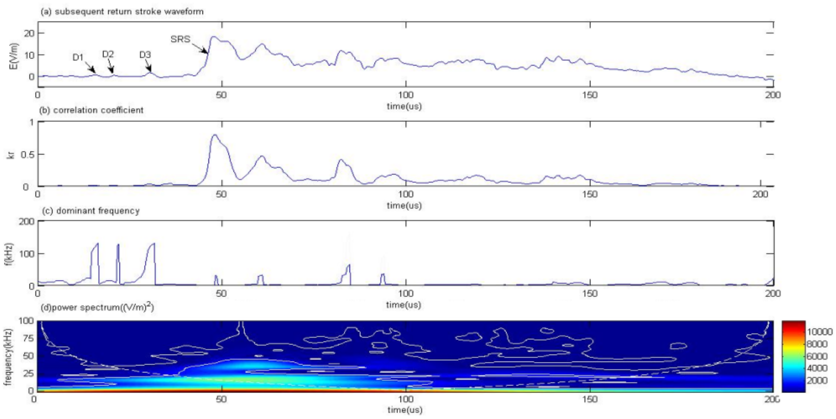

Figure 5. Wavelet Analysis of Subsequent Return Stroke

In each figure, compared plot (a) (the electric or magnetic field waveform) and plot (b) (the wavelet transform correlation coefficient k_r), it can be seen that the time of arrival of initial peaks in plot (a) can be precisely detected by the maximum wavelet transform coefficient in plot (b), especially for the return strokes (e.g. FRS located in the instant of time of about 40 μs in the plot (a) and (b) of Figure 4). As the accuracy of the stroke time is determined by the random errors in the measured time of arrival of the stroke pulse used in ToA calculation, the NLDN system had a standard deviation of about 1.5 μs [11]. In our research, the faulting time could be accurate to hundreds of nanoseconds. This error is suitable for our lightning location system as it was in a good condition within 1 μs [12]. As a result, the initial peak field $x(\tau_p)$ and the dominant frequency component $\bar{\omega}_p$ can be determined according to τ_p in plot (a) and (c).

The frequencies of the power spectrum peak for both first and subsequent return stroke are less than 15kHz, which is also in reasonable agreement with the results in [6].

In plots (d) about power spectrum, in addition to wavelet power spectrum of the time and frequency domain, signals significance test and cone of influence were also computed. Thick contours enclose regions of greater than 95% confidence for a red-noise process with a lag-1 coefficient of 0.72 [4]. The cone of influence is the region of wavelet spectrum in which edge effects become important and is defined as e-folding time for autocorrelation of wavelet power at each scale.

Table 1 presents the statistics of the wavelet transform for 19 PB pulses, 37 stepped leaders, 8 dart leaders in three different negative flashes; 73 first return strokes and 52 subsequent return strokes in 28 flashes. The values of initial peak field, dominant frequencies, the peak energies of power spectrum and frequencies of peak power spectrum of different lightning events are shown separately.

The dominant frequencies of the pulses and frequencies of the power spectrum peak of LEMP radiated by PB pulses lie 184 to 842 kHz and 167 to 434 kHz, and that of leaders are 126 to 665 kHz and 134 to 506 kHz, respectively, which are much higher than that radiated by the return strokes.

Table 1. Statistics of the Laplace Wavelet Transform for Lightning Events

	PB pulses	Leaders	First strokes	Subsequent strokes
Electric field				
Initial peak (V/m)	2-8	2-4	20.1-29.2	16.5-25.5
Dominant frequency (kHz)	184-842	126-665	34-94	8-25
Power spectrum				
Peak energy ((V/m)2)	944-1127	409-716	6914-25724	11710-18233
Frequency (kHz)	167-434	134-506	12-79	6-15

The frequency of field initial peak of first return strokes lies between 34 to 94kHz with the frequency distribution of power spectrum peak of 12 to 79kHz, whereas the frequency spectral range of subsequent return strokes is from 8 to 25kHz with frequency distribution of power spectrum peak of 6-15kHz. Note from Table 1, the dominant frequency of initial peak field of first strokes is generally 3 to 4 times higher than that of subsequent strokes. This suggests that the higher frequency emission may due to the effects of branching channel in first strokes [13, 14].

In this table, the initial peak fields and peak energies are also shown. Comparing these values of different transient lightning events under consideration reveals that the return strokes are the strongest source of energy at lower frequencies.

According to the frequency at the initial peak pulses and peak energy based on the Laplace wavelet transform, the Laplace wavelet transform is a useful method for distinction of different lightning events in analyzing flashes with multiple strokes.

5. Conclusion

In this study, a wavelet transform analysis of the electromagnetic field waveforms corresponding to 19 preliminary breakdown pulses, 37 stepped leaders, 8 dart leaders, 73 first and 52 subsequent return strokes has been presented. The primary focus is on parameters relevant to each lightning event, such as the time of arrival, the dominant frequency, and the value of the initial peak field, the peak energy of power spectrum, and the frequency of power spectrum peak. It is observed that the time of arrival of the initial peak of return stroke in a transient lightning electromagnetic field wave can be precisely located by the wavelet transform coefficient, which is very useful in the ToA lightning location calculation. Besides, the PB pulses radiate predominantly at higher frequencies as that of leaders in the frequency range of about 100kHz to 1MHz, and the dominant frequency of first return strokes which is less than 100kHz is generally about 3 to 4 times as larger as that of subsequent return strokes in general. The increase is mainly caused by the presence of tortuosity and branches along the first return stroke channel.

Using Laplace wavelet transform to decompose the lightning electromagnetic field waveforms in time-frequency space, the time of arrival of the initial peak field can be located precisely, and the domain frequency of the initial peak and the frequency of power spectrum peak are different among different lightning events. The time information is useful in ToA lightning location calculation and prediction system, and the frequency information can be used to mitigate data congestion in real time and to obtain better information in lightning prediction and location system. Therefore, the Laplace wavelet transform is a rational method to identify the features of LEMP in time-frequency space. Further details about the characteristics and classification of these lightning events will be discussed in future investigations.

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