Characteristics of acoustic signals from lightning using a microphone array observation system

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Abstract. The acoustic signals of thunder provide information on the lightning channel, such as frequency, power spectra density, and images. In this study, to analyze the frequency variation in acoustic signals of thunder and to reconstruct the 3D lightning channel imaging, the short time Fourier transform (STFT) and differential time of arrival (DTOA) methods were used. The results showed that the frequency for four microphones varied from 4.88 Hz to 175.78 Hz. Furthermore, the range of power spectra density values for the four microphones was between -0.59 dB/Hz and -28.31 dB/Hz. This system can reconstruct 3D lightning channel imaging.

1. Introduction
Lightning generates not only electromagnetic waves but also shock waves of thunder, which travel at the speed of sound [1], spread huge energy to the surrounding environment and transform the acoustic signals from the lightning channel [2]. The largest amplitudes of the acoustic signals are usually associated with the return stroke of the lightning discharge. The acoustic signals produced by lightning discharge have been analyzed in the time and frequency domains to identify thunder features [3-5]. Furthermore, the acoustic signals of thunder also provide information on the image of the lightning channel. The purpose of this preliminary study was to analyze the frequency variation in acoustic signals of thunder and to reconstruct the lightning channel imaging.

2. Methods
In this study, to analyze the frequency variation in acoustic signals of thunder and to reconstruct the 3D lightning channel imaging, the short time Fourier transformation method and the differential time of arrival method were used, respectively, as described in the following section.

2.1. Spectrogram
Short time Fourier transform (STFT) is a powerful method for displaying low-frequency variations in the spectrum. The recorded acoustic signals of thunder were split into narrow time windows, and then, by introducing Hann or Hamming windows, each window was evaluated by fast Fourier transform. The power spectrum produced by a short line segment with the same power (dB/Hz) as the lightning discharge is similar to the power spectrum of the sound of thunder [4].
2.2. Differential time of arrival

The acoustic signals of thunder were recorded simultaneously by four different microphones (for convenience ‘mic’ refers to microphone). Next, to obtain the differential time of arrival (DTOA) at different microphones, all acoustic signals were examined by cross-correlation.

![Figure 1. Schematic diagram of a differential time of arrival of thunder signals [6]](image)

The time difference between signal 2 \( (t_2) \) and signal 3 \( (t_3) \) is \( \Delta t = |t_2 - t_3| \). The azimuth \( (\beta) \) and elevation \( (\alpha) \) can be resolved as follows:

\[
|DH| = v \cdot \Delta t \tag{1}
\]

\[
v = 322 + 0.6 \text{ T} \tag{2}
\]

where \( v \) is the speed of thunder sound propagation.

\[
\cos(\angle ODH) = \frac{|DH|}{|OD|} = \frac{v \cdot \Delta t}{L_2} \tag{3}
\]

\[
\cos(\angle EDH) = \frac{|DE|}{|DH|} = \frac{v \cdot \Delta t}{L_2} \tag{4}
\]

\[
|DE| = |DF| \times \cos(\angle GOF) \tag{5}
\]

\[
\frac{v \times \Delta t}{L_2} = \frac{|DH| \times \cos(\angle HDF) \times \cos(\angle GDF)}{|DH|} = \cos \alpha \sin \beta
\]

\[
L_2 \times \cos \alpha \cos \beta = v \times \Delta t = v \times |t_2 - t_3| \tag{7}
\]

\[
E_{21} : L_1 \times \sin \alpha = v \times |t_2 - t_3|
\]

\[
E_{23} : L_2 \times \cos \alpha \cos \beta = v \times |t_2 - t_3|
\]

\[
E_{24} : L_2 \times \cos \alpha \sin \beta = v \times |t_2 - t_4|
\]

\[
E_{31} : L_1 \times \sin \alpha \times L_2 \times \cos \alpha \cos \beta = v \times |t_3 - t_4|
\]

\[
E_{34} : L_2 \times \cos \alpha \cos \beta \times L_3 \times \cos \alpha \sin \beta = v \times |t_3 - t_4| \tag{8}
\]
3. Observation and Data

Acoustic signals of thunder were recorded using a microphone array observation system located in Padang, Indonesia (-0.912° N, 100.418° E). The system consisted of four condenser microphones with a frequency range of 20 Hz-20 kHz while an oscilloscope controlled by a computer was used to capture the thunder sound. Furthermore, the four acoustic signals were amplified by an audiophile vacuum tube preamplifier with gain at 26-60 dB and maximum output at \( \infty \)-10 dB. The record length was 20 s with a pre-trigger of 10% of the record length and a sampling rate of 1 MS/s. A schematic of the microphone array observation system is shown in Figure 1, with the distance between the microphones at 2 m. Due to limited data, in this study one acoustic signal of thunder sound recorded at 6:48:37 PM, on September 8, 2018, was analyzed.

4. Result and Discussions

The recorded acoustic signals of thunder are shown in Figure 2a. The frequency and power spectra density of the thunder signals were obtained using STFT for each microphone, as displayed in Table 1 and Figure 3. From Table 1 it can be seen that the ranges of minimum and maximum frequency values for the four microphones were 4.88-29.30 Hz and 107.42-175.78 Hz, respectively. The ranges of minimum and maximum power for the four microphones were 20.36-28.31 dB/Hz and 0.59-2.05 dB/Hz. Table 1 indicates that the frequency and power spectra density of the thunder signal depend on the arriving direction of the acoustic signal from the lightning channel sensed by each microphone. The frequency of the acoustic signal of thunder was below 200 Hz. The same result has also been reported by Abegunawardana et al. [4].

Furthermore, Figure 2b shows the expanded acoustic signals of thunder in Figure 2a, recorded simultaneously by four microphones, namely mic 1, mic 2, mic 3, and mic 4, respectively. The azimuth and elevation angles were obtained by calculating the different times of arrival for each microphone used DTOA and cross-correlation to find the peak values of the four microphone signals. The lightning channel image can be reconstructed from the thunder signals, as shown in Figure 4. From Figure 4 the direction (azimuth and elevation) and time order of location from the lightning channel can be seen.

![Figure 2](image-url)

**Figure 2.** (a) Acoustic signal of thunder recorded by a microphone array. (b) Expanded time of acoustic signals of thunder.
Table 2. Spectrogram of the acoustic signal of thunder for four microphones

| Acoustic Signal | Frequency (Hz) | Power spectra density (dB/Hz) |
|-----------------|----------------|-------------------------------|
|                 | Min | Max   | Min | Max   |
| Mic 1           | 4.88| 175.78| -28.31| -1.61 |
| Mic 2           | 29.30| 131.84| -20.36| -1.49 |
| Mic 3           | 4.88| 107.42| -20.73| -0.59 |
| Mic 4           | 4.88| 117.19| -21.06| -2.05 |
Figure 3. Spectrogram of thunder signals using STFT

Figure 4. Lightning channel imaging
Analysis of the frequency variation in acoustic signals of thunder and reconstruction of the lightning channel imaging using a microphone array observation system were done. The results show that the frequency variation for the four microphones ranged from 4.88 to 175.78 Hz. Next, the range of power spectra density values for the four microphones was between -0.59 dB/Hz and -28.31 dB/Hz. The system can reconstruct the lightning channel direction. More data are needed to improve the understanding of the acoustic signature of the lightning channel.

5. References
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