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Reconstruction of lightning channel geometry by localizing thunder sources

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ABSTRACT

Thunder is generated as a result of a shock wave created by sudden expansion of air in the lightning channel due to high temperature variations. Even though the highest amplitudes of thunder signatures are generated at the return stroke stage, thunder signals generated at other events such as preliminary breakdown pulses also can be of amplitudes which are large enough to record using a sensitive system. In this study, it was attempted to reconstruct the lightning channel geometry of cloud and ground flashes by locating the temporal and spatial variations of thunder sources. Six lightning flashes were reconstructed using the recorded thunder signatures. Possible effects due to atmospheric conditions were neglected. Numerical calculations suggest that the time resolution of the recorded signal and 10 ms^{-1}error in speed of sound leads to 2% and 3% errors, respectively, in the calculated coordinates. Reconstructed channel geometries for cloud and ground flashes agreed with the visual observations. Results suggest that the lightning channel can be successfully reconstructed using this technique.

1. Introduction

Lightning produces a shock wave as the medium expands suddenly due to extremely high temperature variations along the lightning channel. A shock wave, which is traveling at a high speed compared to the speed of sound (Few, 1995), after spreading much of its energy to the surrounding, transforms into audible and non-audible thunder signals within a few meters or less from the lightning channel (Few, 1970). Large amplitudes of thunder signatures are usually associated with the return stroke. However, thunder signatures associated with other events in the channel also emit sound signals with amplitudes high enough to be recorded. The thunder signal recorded provides information on the random orientation of the lightning flash. The localization of a source of thunder and the reconstruction of thunder channel geometry are complicated processes due to the complexity of a thunder storm. Simultaneous measurements of thunder signals at three or more stations could be used to localize the source of a particular event. Two different techniques have been used in the past for the localization of thunder sources.

A more accurate method capable of locating many thunder sources in a thunder channel is the ray tracing method. The time difference between the arrival of a thunder signature at different microphones in a network, typically tens of meters apart, is used to determine the direction of the incoming sound wave at the network. The directional rays are mathematically traced back to the source, considering the acoustic features and atmospheric conditions. The accuracy of the ray tracing method has been discussed (Few and Teer, 1974). Reconstruction of lightning channel geometry using the time of arrival of thunder signatures has been discussed in detail (MacGorman et al, 1981; Nakano, 1973, 1976; Teer and Few, 1974; Weber et al, 1982).

Another technique called the thunder ranging method (Bohannon, 1978), which provides a coarse view of a thunder channel, has been discussed for the location of a thunder source. It has been shown (Few, 1982, 1995) that thunder signals become spatially incoherent at microphones which are separated by distances greater than ~100 m, due to differences in perspective and propagation path. However, gross features such as claps remain coherent for microphones separated by distances of the order of kilometers.

The accuracy and problems of the ray tracing technique have been discussed (Few and Teer, 1974). It has been shown that acoustically reconstructed channel geometries were in close agreement with photographs of the channels taken below the clouds. The effects of wind, temperature and the curvature of the wave front on the accuracy and on the determination of the direction of propagation of thunder towards an array of microphones have been discussed.

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Several attempts for reconstruction of thunder channel geometries have been reported in literature. The thunder channel of a single lightning strike (Nakano, 1973), 14 events from a single storm (Nakano, 1973), with only a few points per channel, and all events during an active period of a thunder storm cell (Teer and Few, 1974) have been reconstructed. Furthermore, an analysis of a whole storm by acoustic channel reconstruction has been performed and statistics of different storm systems have been compared (MacGorman et al, 1981).

In this study, a thunder source localization and lightning channel geometry reconstruction system (Bodhika et al, 2011) has been developed and experimentally tested with three microphones. Three signals from the microphones were recorded and the time shifts between each pair of microphones for correlated phase points of the three signals were calculated (cross correlation method). The time lag between the light and thunder signals was measured manually. A mathematical model was developed to calculate the location of the thunder source using the time lapse of the thunder signal arriving at each pair of microphones. The accuracy of the constructed model was estimated using numerically generated thunder signals. Thunder channel geometries of six flashes have been reconstructed using the model. Reconstructed lightning channel geometry, whether it was cloud to cloud or cloud to ground, was in agreement with visual observations, which were noted when taking data. One drawback of the three-microphone system is the generation of an unwanted extra solution for the location of the source. However, this extra solution was easily eliminated due to mismatch of the solution in this study. The error in measured time difference between the light and sound signals reaching the observer makes the highest contribution to the error of the calculated source coordinates. These drawbacks can be improved using a model of five microphones.

2. Theoretical model

A model constructed using thunder signals recorded by several microphones to locate the source point is presented here. Three models with three, four and five microphones, respectively, are discussed and the three-microphone system is used to reconstruct the thunder channel geometry. In this acoustic technique, a thunder signal recorded was divided into a series of short contiguous time segments, and a cross correlated phase point for relevant time segments was identified. For each time segment, a peak common to all microphones and well isolated, which could be identified matching the shape of the signals, was selected as the cross correlated phase point. For some time segments, especially at the latter part of the signal, there were no correlated phase points. The time lags between the cross correlated phase points were obtained from the recorded signals and used in the model for calculation of location of thunder sources. The set of points generated in this manner from the complete thunder record delineate the geometry of the lightning channel.

2.1. Thunder source localization by three microphones

The system with three microphones has been briefly discussed previously (Bodhika et al, 2011). Three microphones (P, Q and R) were located at P (p,0,0), Q (0,q,0) and R (0,0,r) with respect to the origin O, and the position of the sound source was taken at S (x,y,z) as shown in Fig. 1(a). A wave front originating from the sound source at S (x,y,z) reaches the microphones at P (p,0,0), Q (0,q,0) and R (0,0,r) at times t_1, t_2 and t_3 respectively. If the velocity of sound is v, then:

$$[(x-p)^2+y^2+z^2]^{1/2}-[x^2+(y-q)^2+z^2]^{1/2}=v(t_1-t_2)=vt_{12} \tag{1}$$

$$[(x-p)^2+y^2+z^2]^{1/2}-[x^2+y^2+(z-r)^2]^{1/2}=v(t_1-t_3)=vt_{13} \tag{2}$$

$$[(x^2+(y-q)^2+z^2]^{1/2}-[x^2+y^2+(z-r)^2]^{1/2}=v(t_2-t_3)=vt_{23} \tag{3}$$

Here, $(t_1-t_2)=t_{12}$, $(t_1-t_3)=t_{13}$ and $(t_2-t_3)=t_{23}$ are the times taken to travel the wave front from Q microphone to P microphone, R microphone to P microphone and R microphone to Q microphone, respectively.

Note that only two of the above equations are independent. The distance to point S with respect to O can be written in the form

$$OS=[x^2+y^2+z^2]^{1/2}=vt_0 \therefore\ t_0=[x^2+y^2+z^2]^{1/2}\left(\frac{1}{v}-\frac{1}{c}\right) \tag{4}$$

Here, t_0 is the time difference between the light and sound signals of the lightning flash as measured at the origin, and v and c are the velocities of sound and light respectively.

The known values of p, q and r, sound velocity v and the time differences t_{12}, t_{13}, t_{23} and t_0 can be used with any two equations out of Eqs. (1)–(3), and Eq. (4) to solve for the location of the sound source, S (x,y,z). As the microphone locations p, q and r are known, with the help of recorded thunder data of microphones at P (p,0,0), Q (0,q,0), and R (0,0,r), the time differences t_{12}, t_{13} and t_{23} can be calculated. With careful observation, the time difference, t_0, between light appearance and the first sound signal heard from the thunder reaching the origin can be measured. For the next selected phase points of the recorded signal, t_0 can be calculated using the measured time difference between the first sound signal and the time lapse recorded between the first phase point and the next phase point. Similarly, t_{12}, t_{13}, t_{23} and t_0 can be calculated for

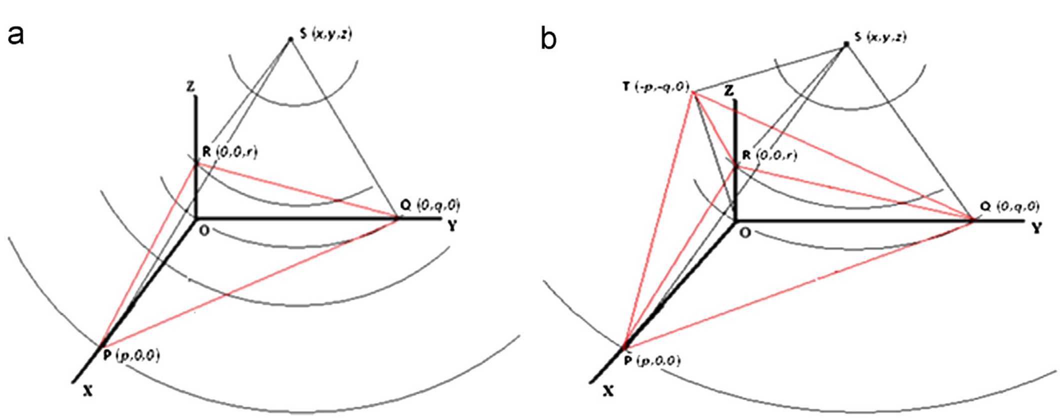

Fig. 1. (a) Geometry of positions of microphones and the thunder source for three microphone system. (b) Geometry of locations of microphones and thunder source for the model with four microphones.