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An improved wave impedance approach for locating close lightning stroke from single station observation and its validation

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ABSTRACT

An improved wave impedance approach for locating close lightning strokes based on single station observation was proposed and practiced. In the approach, a lightning stroke was modelled with an electrical dipole carrying current components in VLF/LF frequency bands. For a lightning stroke, the ratio of its electrical and magnetic fields at ground is theoretically a function of the frequency and distance to the stroke. Distance of the stroke can then be obtained by fitting the theoretical function with the observed data. The approach was examined by applying it to broadband VLF/LF electrical and magnetic fields observed simultaneously at one station for several strokes in ranges of 10–50 km. Furthermore, a prototypal single-station lightning location system (S-LLS), which can be analogized to a modified VLF/LF broadband magnetic direction-finder programmed with the proposed lightning stroke distance determining approach, was built up and tested. Comparisons of individual stroke locations with the local lightning location network show that the S-LLS has a good location accuracy of 0.1–4 km for close strokes in ranges of 15–60 km, but has a poor location accuracy of 12.4–26 km for distant strokes in ranges of 80–130 km.

1. Introduction

A lightning discharge especially the return stroke in a cloud-to-ground (CG) discharge emits strong electromagnetic radiation in VLF/LF bands with its power spectra peaked at about 5–10 kHz. Based on the electromagnetic signal emitted by a lightning discharge, various lightning location systems have been invented to tell when and where a lightning discharge occurred and how strong it was. Knowing when and where lightning discharges just occurred provides people with time in advance to protect themselves and their devices from possible approaching lightning disaster. It also gives convenience to the maintenance of electric-power lines etc. Therefore, lightning location network has been used worldwide by electric power companies for the purpose of protection of their electrical power facilities against lightning.

Most of ground-base lightning location techniques require multiple stations. There are mainly three kinds of multi-station lightning location techniques used world widely: the magnetic direction finder (MDF), time-of-arrival (TOA) and interferometric technique.

A MDF is composed of two orthogonal magnetic loop antennae and one flat plate electrical antenna. Vertical and orthogonal magnetic field loops are used to obtain lightning direction because the ratio of the signals in the two loops is proportional to the tangent of the angle to the lightning source (Krider et al., 1976). The polarity of a lightning return stroke is determined from the electrical signal. A MDF network requires at least two stations and the intersecting point of two directions from the two MDFs gives the source location. Higher accuracy can be achieved if more than two MDFs are arranged.

The TOA technique is based on the fact that a lightning signal arrives at two different stations at different times (Casper and Bent, 1992). A time difference, which means a certain distance difference from the two fix stations to the lightning source, forms a hyperbola. And the intersecting point of 2 hyperbolas from three stations reveals the position of the lightning source. However, two hyperbolas may have two points of intersection when the lightning source is far from the envelope of TOA stations. Therefore a TOA network needs at least 4 stations to make sure that the position of source is unique. In order to take the advantage of both MDF and TOA technique, improved accuracy using TOA/MDF combined Technology (IMPACT) system has been developed and used world-widely (Cummins et al., 1998).

The interferometric technique is based on the fact that phase differences of lightning signal at an antenna array contain the information of the source position, which usually operates at VHF bands between tens and hundreds MHz (Richard and Auffray, 1985). For a given frequency, the azimuth of the source has fixed

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relevancy with phase differences of the antenna array of an interferometer. One interferometer gives the azimuth and elevation of the source, and two are able to add on the distance information.

There are also a few of approaches for locating lightning strokes based on observations at a single station. A single-station lightning locating approach usually involves a lightning source distance finding method plus the MDF technique. There are many kinds of method to get the distance of lightning with a single station and most of them need to be improved further in location accuracy when compared to the sophisticated multi-station lightning locating techniques. Specific pros and cons of these methods are briefed in following paragraphs.

The simplest method to estimate the distance is based on the amplitude of lightning signal, which assumes that there is a fixed distribution pattern of lightning strengths in a thunderstorm and the amplitude of lightning signal in average decreases with distance (Horner, 1960). The lightning locations given by this technique are the thunderstorm rough location rather than the lightning stroke location.

Wave line theory in waveguide is another method to get the distance of lightning (Nagano et al., 2007). The lightning-produced electromagnetic fields propagate in forms of ground wave and sky wave. The sky wave would be reflected between the ground and ionosphere. The signal received by an antenna at ground is the superposition of those ground wave and sky wave with certain wavelengths which meet the waveguide boundary conditions. However, the wave line theory is only valid for medium and short distance in the frequency bands from 3 kHz to 30 kHz (Nagano et al., 2007). From the view of wave line theory, some signal is just reflected by the ionosphere once, and others are reflected between the ground and ionosphere several times. The time differences between those signals are able to tell the distance of lightning source and the height of the ionosphere (Nagano et al., 2007). However, the detecting range and accuracy of this technique highly depend on the diurnal change of the height of the ionosphere. The detecting range of this method is about a few hundred kilometers with accuracy of 10%.

For lightning discharge occurring at large distance, Schumann Resonance has been investigated. Lightning-produced electromagnetic fields will form standing waves in the resonant cavity consisted of the earth surface and ionosphere, which are featured by the superposition of background noise and strong extremely low frequency pulses. Schumann Resonance is a dominant mode when frequency is lower than 100 Hz (Volland, 1995). Wait (1962) first proposed a mode theory on Schumann Resonance. Based on Wait's theory, Nickolaenko and Hayakawa (2002) derived a simplified formula that can be extensively used. Location accuracy of the method based on Schumann Resonance caused by lightning is one hundred times larger than that of NLDN (Boccippio et al., 1998).

The concept of wave impedance was first proposed by Kemp and Jones (1971), which is the ratio of electric and magnetic field amplitude. Korol and Nickolaenko investigated the pattern of wave impedance versus distance and found a routine for source-observer distance derivation. They also pointed out that reflection from ionosphere could be ignored within a short distance observation such as 50 km (Korol and Nickolaenko, 1993).

The phase difference between the electric field and magnetic field produced by a lightning discharge also contains the distance information of the source. At low frequency and short distance the phase difference is $-90°$. When the frequency gets higher or distance increases, the phase difference is close to 0°. This property has been utilized in (Shyets et al., 1997) for locating nearby lightning strokes. The estimated source-observer distances for three events in (Shyets et al., 1997) are 6–7 km, 6–8 km and 8–15 km respectively.

A beam of light with different wavelength travels at different speed within the same medium. So does the lightning signal. The time delay of lightning signal on different frequency is able to tell the distance of lightning. A simple method based on delay time difference was described in (Ramachandran et al., 2007). The locating results of this method have been tested and verified with the World-Wide Lightning Location Network (WWLLN). Its working range was from 3000 to 16250 km with an average deviation of 4.7% within 3500 km. Another difference among different frequency is the group delay, which is related to the lightning distance. The group delay is defined as the differential of phase versus frequency for the lightning signal. However, this method is only valid for distance large than 1000 km with an accuracy of 100 km (Brundell et al., 2002).

In the present paper an improved wave impedance method to locate close lightning at a single station, which is based on the distance and frequency dependences of the ratio of electrical and magnetic fields of the lightning, is proposed and practiced.

2. Single-station lightning locating technique

2.1. Basic theory

The lightning return stroke channel can be viewed as a vertical electric dipole antenna standing on conductive plane, when both the frequency wavelength and the source-observer distance concerned are much longer than the lightning channel scale. Although the lightning stroke channel is usually several kilometres long, its effective length may be shorter than 1 km because the stroke current is found to attenuate significantly as it propagates from ground upwards. Meanwhile, after few milliseconds, the lightning channel may extend into the cloud with horizontal movement of charge in clouds. So the lowest frequency free from much noise may be several hundred hertz. Based on all these aspects, we suppose that the dipole model might be valid for lightning strokes at distances more than 5 km away and for frequency bands from 100 Hz to more than 15 kHz. This is the basis of the present study.

For a dipole current Idl at radian frequency ω, the vertical electrical field E_ω and horizontal magnetic field H_ω at distance r from the observer on ground are given by

$$E_\omega = \frac{Idlk^3}{4\pi\omega\varepsilon}\left[\frac{j}{kr} + \frac{1}{(kr)^2} - \frac{j}{(kr)^3}\right]e^{-jkr} \quad (1)$$

$$H_\omega = \frac{Idlk^2}{4\pi}\left[\frac{j}{kr} + \frac{1}{(kr)^2}\right]e^{-jkr} \quad (2)$$

where $k = 2\pi f/c$ and c is the speed of light.

Both the electrical and magnetic fields attenuate with the growth of distance. The magnitude of either the electric or the magnetic fields cannot tell the distance because the current of lightning stroke is not a constant. However, the ratio of electric and magnetic fields no longer depends on the lightning current and it varies with source-observer distance.

$$\left|\frac{E_\omega}{H_\omega}\right| = G\sqrt{\frac{\mu_0}{\varepsilon_0}}\left|\frac{1}{kr} - \frac{1}{j + \frac{1}{kr}}\right| \quad (3)$$

$$\left|\frac{E_\omega}{H_\omega}\right| \approx G\sqrt{\frac{\mu_0}{\varepsilon_0}} = A, \ \text{for 60~120 kHz} \quad (4)$$

where G is a correction coefficient taking account of the difference in systematic gain between the measuring systems for the electric and magnetic fields. The term (kr) will be much larger than 1 at a