NEW METHOD FOR PASSIVE DETERMINATION THE DISTANCE UP TO LIGHTNING SOURCE

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1. Introduction

The detection and location determination of electric discharges in the troposphere by passive devices is of large interest for flight safety. It is known that each thunderstorm generates a lot of discharges. Not every electric discharge in thunderstorm is accompanied by visible lightning. The word "lightning" means here both visible and invisible electric discharge in thunderstorm, which are accompanied by electromagnetic radiation usually named atmospherics. The task of lightning direction-finding can be solved rather simply by known methods. The greatest difficulties are associated with determining a distance up to a lightning, when measurements are done from a single position, for example, from an airplane. There are several methods developed for this purpose; some of them have been used in operational devices.

The simplest is the *AA* method, which is based on electromagnetic signal's magnitude estimation. On average we know: the more received signal of lightning the less distance between lightning and receiver. Distances can be estimated with 50% error due to statistical nature of lightning power.

The second method is based on the measurement of the electric *E* and magnetic *H* components of the received signal field generated by electric discharge. The distance up to lightning can be estimated by comparison of measured *EH* ratio with the theoretical one for various distances. The *EH* method provides accuracy of about 10 % for distances less than 60 km.

The third known method (*HH*) is based on the measurements of the ratio of two magnetic components via $H_o=H(w_1)/H(w_2)$ at two selected frequencies w_1 and w_2. The method can provide an error of about 10% after averaging H_o over a number of discharges for distance up to 200 km. However, at $R<50$ km the error increases significantly.

The aim of this paper is to present a new method (*EE*-method), which is based on measuring the intensity of two electric components of the field in two orthogonal planes. The research shows some essential advantages of the new method.

2. Fundamentals of the METHOD

Let us assume that the source of lightning radiation is characterised by the equivalent dipole moment $P(\omega)$. According to [2] this assumption is valid if the distance to lightning R is more than 30 km. The expressions of the electric component of a random oriented dipole radiation field in the near-field region (earth conductivity influence is neglected) are calculated according to the field superposition principle. The boundary of near-field region is the distance R between Earth-plane projections of the radiating point and the point of observation. It is determined by the inequality: $R << R_{Earth} / M$, where $M = (kR_{Earth}/2)^{1/3}$ with R_{Earth} is the earth radius, $k=\omega/c$ is wave number, c is the speed of light.

The locations of radiator (lightning channel) and receiver (on aircraft) are given in cylindrical coordinates, and the components of electric field are defined for each projection of the dipole. Let P_X, P_Y, P_Z are the components of dipole P. For each projection of the dipole, the three components of the electric field $\vec{E}$ can be determined. For the vertical component P_Z under the condition that the dipole is located close to the earth, we can write:

$$E_{X_Z} = -\frac{k^2 P_Z}{4\pi\varepsilon_o} f_X(R,\varphi,\psi_o,k) \quad E_{Y_Z} = -\frac{k^2 P_Z}{4\pi\varepsilon_o} f_Y(R,\varphi,\psi_o,k); \quad E_{Z_Z} = -\frac{k^2 P_Z}{4\pi\varepsilon_o} f_Z(R,\varphi,\psi_o,k), \quad (1)$$

where ε_o is the relative dielectric constant; φ, ψ_o, R are the mutual coordinates of source and receiver, and R is the unknown distance as decision variable. The cylindrical coordinate Ψ_0 can be found via: $\cos\psi_o = z/R$, $\sin\psi_o = (R^2 - z^2)^{1/2}/R$ with z is the receiver altitude. Modules of the vertical $|E_{ZZ}|$ and the horizontal $|E_{XY_Z}| = \sqrt{|E_{X_Z}|^2 + |E_{Y_Z}|^2}$ component of the (dipole radiation) electric field can be found from (1). After substitution and mathematical transformations we obtain the value $E_0^2 = (|E_{Z_Z}|/|E_{XY_Z}|)^2$, which can be represented as

$$R^8 + m_1 R^6 + m_2 R^4 + m_3 R^2 + m_4 = 0, \quad (2)$$

where $m_1 = -z^2(E_0^2 + 2) - \frac{1}{k^2}$; $m_2 = \frac{z^2}{k^2}(2 - 3E_0^2) + z^4(1 + E_0^2) + \frac{1}{k^4}$;

$$m_3 = 3\frac{z^4}{k^2}(1 + E_0^2) - 3\frac{z^2}{k^4}(2 + 3E_0^2); \quad m_4 = 9\frac{z^4}{k^4}(1 + E_0^2).$$

Thus, the distance between the lightning and airborne receiver can be determined by measuring the ratio of electric field strength modules in vertical and horizontal planes at one frequency. The algorithm, which has been developed, uses the magnitude of the electric strength of the radiated field as informative parameter. We therefore choose the frequency band where the main energy is concentrated. Maximum spectrum density of lightning discharges is usually near 3-10 kHz. Near-field region for this frequency band is limited to 100-150 km distance. The equation (2) has an unambiguous solution, and gives an estimate of the distance up to lightning discharge at the interval 30-150 km for chosen frequency band.

3. Accuracy of the METHOD

The accuracy of distance estimation by the *EE*-method depends on several reasons. Among them:

1) the error due to the assumption that the equivalent lightning dipole is located near the Earth surface;
2) the error due to a deviation of the equivalent dipole from vertical;
3) the error of measuring the electric field strength.

The error distribution obtained by statistical modeling is shown in Fig. 1. It fits to the Gaussian distribution with parameters which depend on the reasons enumerated above. Let us consider each of three reasons separately.

In order to lower the influence of the accepted assumption on the total error, it would be good to know the altitude of the discharge source over the Earth surface. This altitude is unknown, but some a priori statistic information is available. Let us assume that the source altitude is Gaussian distributed with specified mean and variance. Then we can estimate the distance up to lightning with the developed algorithm and calculate the error for the determined distance and specified mean source altitude using mathematical models for the components of the discharge radiation field. The next step is correction of the initial estimate using the calculated error. The error due to the first factor versus distance is shown in Fig. 2 without correction (curve 1) and with correction (curve 2).

In fact the *EE*-method has been developed for vertical lightning. That is why a deviation of the equivalent dipole from vertical position can contribute to an essential error. In order to exclude this factor it is necessary to identify and measure only vertical discharges. That can be done, for example, by auxiliary measuring of the vertical component of magnetic field, which for vertical lightning should be zero.

There are no ideal vertical lightning channels in nature, so it is impossible to exclude this type of error completely. Fig. 3 shows the error due to non-verticality as a function of distance between radiator and observer at different deviation angles of lightning channel from vertical position. Curve 1 corresponds to deviation of 5^o, curve 2 - 10^o, and curve 3 - 20^o.

The error of distance estimate depends also on the accuracy of measuring the electric field strength on the background of interference and receiver noise. A technique of averaging multiple measurements of observables during the same lightning discharge can be used in order to lower this error. A possible way of averaging follows from the least-squares procedure. In this case the ratio of vertical to horizontal component of the electric field strength is determined by the following expression:

$$E_0 = \sum_{i=1}^{N} E_{Z_Z} E_{XY_Z} / \sum_{i-1}^{N} E_{XY_Z}^{2} \ . \qquad (3)$$

The influence of accuracy measuring ratio E_o onto the error of distance estimation is shown in Fig. 4 without averaging (curve 1) and with averaging by using the least-squares procedure (curve 2).

Having taken into account the proposed measures for increasing the accuracy, the total accuracy of the *EE*-method of distance estimation up to lightning is illustrated in Fig. 5 as function of the distance at a deviation angle of 5^o and error in E_o measurements of 10%.

4. Discussion

The accuracy of the proposed *EE*-method for the determining of the distance up to lightning from one location depends on several factors. One of them is the assumption that the altitude of the equivalent lightning dipole equals zero. The effect of this factor becomes less when the distance increases.

The second component of the error is contributed by the deviation of the equivalent dipole from vertical position. This error can be reduced by the identification of vertical discharges. The averaging can reduce the error of electric field strength measuring.

A redistribution of influences of different factors onto the total error takes with increasing distance. According to our analysis results, the first reason is predominant at short distances. The contribution of the second reason becomes also less if the distance increases but it stays significant during all ranges of measured distance. Unfortunately, the spatial position of the lightning channel is a priori unknown to the observer to make a correction. However, in general, it can be determined with auxiliary measurements.

Comparison of the accuracy of *EE*-method with other methods, described in introduction, demonstrates the advantage of the proposed method. Note that the EE-method can be implemented on one frequency or using a spectrum of frequencies with special processing to make more reliable measurements.

The proposed *EE*-method is suitable to improve the techniques of estimating the distance to lightning discharge from one location, for instance, in aircraft equipment.

Essential breakthrough in the considered field should be achieved using the synergy of different methods.

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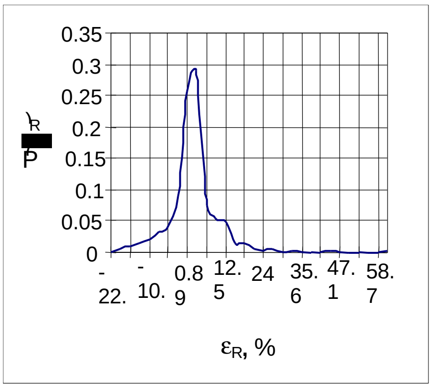


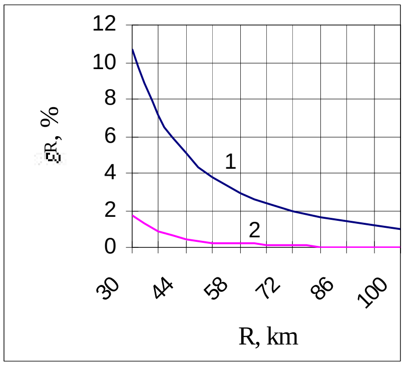
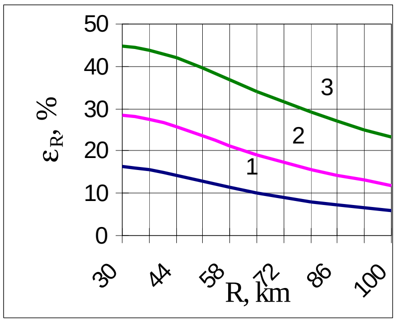
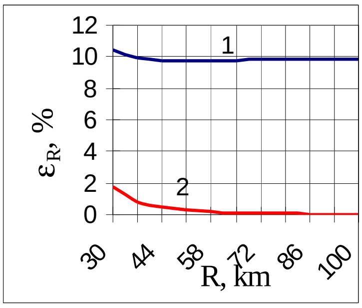


Fig. 1. Density distribution of relative error of measuring distance up to lightning.

Fig. 2. Error due to the assumption of zero altitude of discharge versus distance without correction (1) and with correction (2).





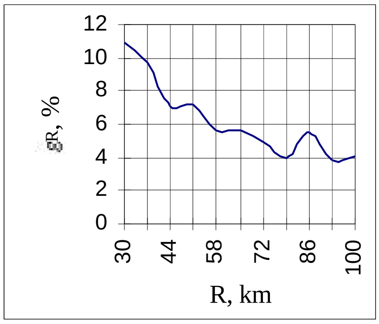


Fig. 3. Error caused by deviation of lightning channel from vertical. Deviation angles : 5, 10 and 20 degrees (1, 2 and 3 respectively)

Fig. 4. Error introduced by inaccuracy of electric field strength measuring.

Fig. 5. Total error of estimating distance up to lightning by EE-method versus distance obtained by statistical modeling.

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