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LIGHTNING STROKE PASSIVE LOCATION BY ATMOSPHERICS ANALYSIS IN THE HOP MODEL FRAMES

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The problem of lightning location from single station observation is considered based on the hop model of lightning electromagnetic radiation pulse propagation in spherical waveguide “Earth – ionosphere”. Some new methods are discussed to estimate the delays of the ionosphere reflected waves with respect to the ground wave. These delays give raise to the undetermined system of equations where unknown quantities are the distance and the effective reflecting heights of ionospheric waves. Some methods to remove the uncertainty based on approximation of difference of effective reflecting heights are considered. Program codes in Matlab to process atmospherics are developed. Proper examples concerning of really registered signals are carried out.

Keywords: thunderstorm, lightning, electromagnetic radiation, atmospherics, hop model, ionospheric waves, delays, distance evaluation

1. Introduction

Lightning discharges are significant causes of interruptions or damages in almost every from earth-based structures, especially electrical or electronic systems that are exposed to influence of thunderstorms. Damages and interferences in the ground structures are caused by cloud-to-ground lightning strikes mainly. The problem is particularly severe for electric power lines, fuel or gas pipelines utilities that have exposed assets covering large areas. The lightning induced mine explosions are in this list too. In addition, cloud-to-ground lightning discharges give rise to significant part of forest fires (up to 70% in poor populated territories), so as the primary hazard is forest fires inflammability detection.

Cloud-to-ground discharges make up a third of all lightning strikes: the remaining two thirds occur within clouds or between clouds. The cloud-to-cloud discharges can provoke numerous faults in airplane body and avionics. Important role in it belongs to secondary side-line effects of lightning appearance, including severe air turbulence, heavy hail and/or shower, and electromagnetic radiation, rather than the direct lightning strike into fuselage itself.

Thus, detection and location of lightning discharges are the serious scientific and technical problems. Appropriate technical systems would be based on passive location principles, namely, receiving and processing of atmospherics, or transient pulses created by intrinsic electromagnetic radiation of individual lightning channel.

There are two ways to decide this problem. The first is to develop a network consisting of great number of receivers, data transmission lines and common processing centre. During 1980–1990 the Lightning Detection Networks (LDN) have been created in some economically powerful countries (USA, Austria, England, for example). The network consisting of 200 receiving stations evolves in China started from 2008.

LDN operational principle is based on measurements of the “times of arrivals” (TOA) of atmospherics to the different receiving points whose geographic coordinates are fixed. Then, differences of TOA are calculated and solutions of so-called inverse geodesic problem are found resulting the lightning discharge coordinates.

Proper scheme is shown on Figure 1 [1] where the ciphers designate accordingly:
1) receiving sensors transmit data to satellite; 2) satellite relays information to Earth station; 3) data is transmitted to processing centre via landlines; 4) this centre processes data; 5) processed data relays back to satellite; 6) lightning discharge data is displayed within few seconds after the strike. Receiving sensors are marked with white dots on US map showed on Figure 1. The sensors in LDN are typically separated by 50–400 *km*.

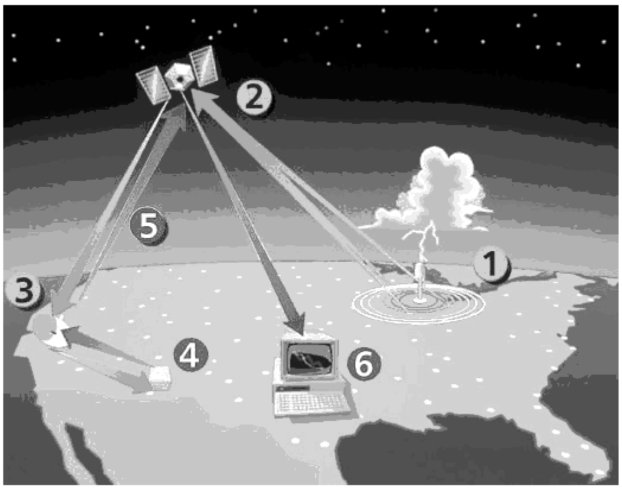

Figure 1. Operational principle of LDN

The alternative way is the system for lightning location from single station observations. The bearing indication on to the lightning discharge is decided by processing of the individual atmospherics based on direction finding methods. The main problem is evaluation of the distance from the discharge. It can decide based on the certain inherent features extracted from the atmospherics. The latter propagates in Earth-ionosphere waveguide, therefore, these features are reflected the properties of that trace.

With rigorous mathematic point of view, evaluation of the distance is covering the functional operator reflecting the space of atmospherics generated by lightning with the same distances and received by the same sensor to the same quantity. All the methods of single-point distance evaluation can be divided into two groups. First of them include “local” methods where estimation of distance is formed from the quantity of signal in neighbourhood of some characteristic point (as maximum amplitude of the temporal form or maximum spectral density of atmospherics). Fatal shortcomings of these methods are dependence from magnitude and kind of the current in the lightning channel. Nevertheless, the local methods put into the operational principles of devices adopted for ground [2] and airborne [3] applications.

2. Hop Model

The second group consists of “integral” methods where the distance estimation is calculated by analysis all the atmospherics temporal form. If the distance from lightning discharge to receiving point is not larger than 1500–1800 *km*, a hop model of atmospherics propagation in spherical Earth – ionosphere waveguide would be discussed. It is supposed the received atmospherics consists of superposition from a ground wave and some waves reflected by ionosphere. The inherent features of the appropriate distance in this case should be appeared as delays or times of arrivals (TOA) of that reflected waves.

The 2-hop model sketch is illustrated on Figure 2. Electromagnetic radiation initiated from point A propagates to receiving point B in a spherical waveguide. The lower wall of it is surface of the Earth, and the upper wall disposes within D-layer (day time) or E-layer (night time) of ionosphere. Receiver in B registers the process of interaction of the ground wave $E_g(t)$ passed the distance r_0, and a few ionospheric waves. Only two waves from them are shown on Figure 2. The single-hop wave $E_{i1}(t)$ and twice-hop wave $E_{i2}(t)$ pass the ways signed as r_1 and r_2 being reflected from the effective heights H_1 and H_2 with angles θ_1 and θ_2 accordingly.

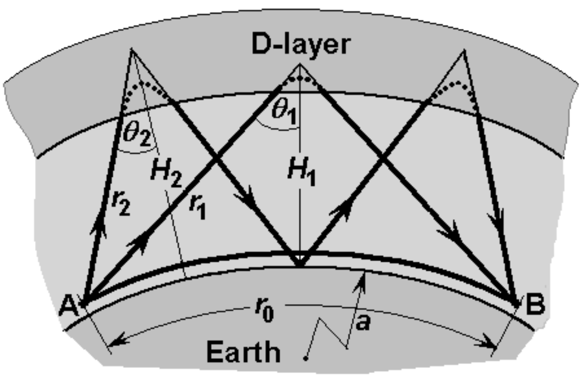

Figure 2. The hop model of the ionospheric waveguide

The input signal of receiver can be written as

$$u(t) = E_g(t) + \sum_{n=1}^{N} E_{in}(t) = I(0,t) * [h_c(0,t) * h_g(t) + \sum_{n=1}^{N} h_c(\theta_n, t) * h_{in}(t)], \quad (1)$$

where sign $*$ is a symbol of convolution, $I(0, t)$ is temporal form of the current pulse in lightning channel base; $h_c(\theta, t)$ is pulse function of lightning channel radiation to the direction setting by angle θ; $h_g(t)$, $h_{in}(t)$ are pulse functions of traces for ground wave and n-th ionospheric wave accordingly. Evidently, the reflected waves $E_1(t)$ and $E_2(t)$ are delayed versus ground wave by times signed further as τ_1 and τ_2 correspondingly.

From geometrical properties of the waveguide one can obtain the system of equations,

$$T_n = (1 - 2Z_n \cos R_n + Z_n^2)^{1/2} - R_n, \quad n = 1, 2, \ldots \quad (2)$$

where $T_n = c\tau_n / 2na$, $R_n = r_0 / 2na$, $Z_n = 1 + H_n / a$ are normalized delays, distances and effective reflection heights accordingly; $c = 2{,}998 \cdot 10^8$ *m/sec* is light velocity in vacuum, $a = 6378$ *km* is radius of the Earth.

As the two-hop model is considered the system (2) consists of two equations, but three unknown quantities are in it, namely, the distance and ionospheric waves effective heights of reflection. Therefore, this system is undetermined since the number of equations is lesser on 1 than the number of unknown quantities. Some possibilities to expand the system will be examined later.

3. Evaluation of Delays

Signal (1) under consideration has formed by convolution. As an example, Figure 3 at the top shows the atmospherics registered in daytime by a certain sensor belonged to LDN. The distance from lightning was estimated near 600 *km*. It is obvious that visual identification of separate waves in this signal is most likely impossible.

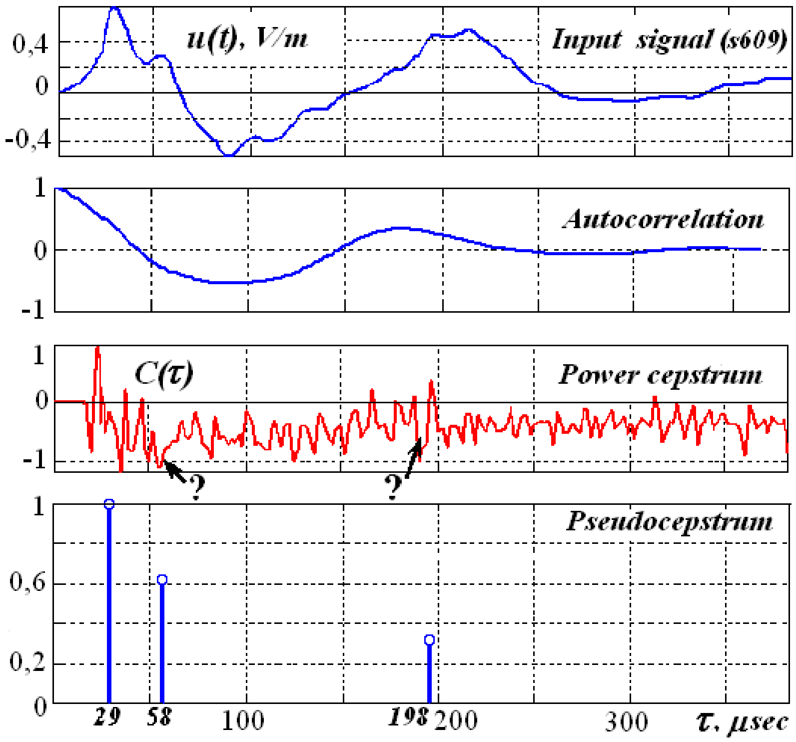

Figure 3. Atmospherics and some results of processing of it

Collection of methods to estimate delays of internal structural components in that signals is rather poor. A common way used is to calculate the autocorrelation function based on Fourier transformation (FT) as follows [4]:

$$\mathrm{ACF(t)} = \mathrm{FT}^{-1}\{|\mathrm{FT}[u(t)]|^2\}, \quad (3)$$

where FT^{-1} is a symbol of inverse Fourier transformation. The function (3) is illustrated as the second row of Figure 3. Estimation of delays from it is rather impossible too. Perhaps, it can be explained by sufficient differences in the forms of ground and ionospheric waves.

As a signal corresponds with the convolutional model one can attempt to estimate delays applying the cepstrum analysis [5]. It is conceptually based on three steps:

(a) calculation of direct FT to find the signal complex spectrum $S(\omega)$;
(b) calculation of the logarithmic spectrum $S_{\log}(\omega) = \log S(\omega)$;
(c) calculation of inverse FT from $S_{\log}(\omega)$.

Combining these operations we can obtain the following:

$$c(\tau) = \mathrm{FT}^{-1}\{\log (\mathrm{FT}[u(t)])\}. \tag{4}$$

The result (4) is known as the complex cepstrum of the signal $u(t)$. The values assigned as τ are named quefrencies. Physically, anyone from quefrencies has a meaning as some delay. In many cases it is sufficiently to operate with power cepstrum

$$c_{\mathrm{p}}(\tau) = \mathrm{FT}^{-1}\{\log (|S(\omega)|^2)\} \tag{5}$$

or real cepstrum only neglecting by phase information, which is contained in the complex spectrum $S(\omega)$ or logspectrum $S_{\log}(\omega)$ [5].

It is known that cepstral algorithms are worked satisfactorily for the linear models only, as long as convolutional components of signal are mapped onto logspectrum additively. Moreover, they run successfully if the next conditions are kept: (i) signal has sufficient duration; (ii) inherent structure of it is periodical; (iii) signal-to-noise ratio is sufficiently large. As a rule, atmospherics are incompatible with conditions (i) and (ii). The third row in Fig. 3 shows the power cepstrum of the analysed atmospherics. It is seen that estimation of delays from cepstrum in this case is actually impossible.

It would be supposed that considered methods works unsatisfactorily owing to the FT, as a mathematical operation, possesses certain lacks itself. Particularly, it is known that FT is not incompletely adequate for non-stationary signal processing [4, 5].

We have been investigated the methods to expose the inherent structure of lightning electromagnetic radiation. One from them is considered in [6] founded on computing of adiabatic invariants of atmospherics. We have been proposed also the new, non-Fourier method for estimation of delays which was published [7] as pseudocepstral analysis.

The algorithm based on Huang-Hilbert transformation [8] of logarithmic spectrum $S_{\log}(\omega)$ is expounded in detail in [7]. The result of it is illustrated in a lower row of Figure 3. The calculated quantity is named pseudocepstrum. The δ-pulses positions showed on this plot are equivalent with quefrencies in (5). The signs of the pulses are ignored owing to neglecting of phase information. The pulses indicate consequently the following moments:

1) the electric current pulse propagating along lightning channel is reached the top of the channel; electromagnetic radiation from the channel is ended;
2) one-hop ionospheric wave is arrived to the observation point;
3) two-hop ionospheric wave is arrived.

Proceeded from these data, the inverse problem concerning geometry of waveguide Earth – ionosphere would be decided. It is important contribution to theory of single-station lightning strokes passive location on the basis of the own EM radiation analysis.

4. Evaluation of Distance and Effective Heights

After estimation of delays it should be reverted to the system of equations in (2). Unknown quantities in it are the distance and effective reflecting heights of ionospheric waves. As it was mentioned the system is undetermined. We have been investigated some methods to find additional conditions closely linked the unknown quantities.

One possibility is based on approximation of difference of effective heights having considered as the function of the distance r_0. To build that function it is necessary to know how electron density N_e and collision frequency ν_e of ionosphere change versus heights. The exponents are supposed frequently in theory but it requires special analysis. These parameters depend on daily-times and geographic positions of atmospheric propagation traces. That is why using of this method in practice is rather doubtful without *a priori* knowledge concerning ionospheric parameters and needs in additional examination.

It is desirable the method of elimination of defects in (2) is not linked with N_e and ν_e characteristics. The corresponding algorithm for estimation of distance r_0 and heights H_1 and H_2 is offered below. It is based on some restricts for solutions of (2) which follow from physical consideration of propagation in Earth – ionosphere waveguide:

1) reflecting heights lie within D-layer in daytime or E-layer in night time then

$$H_0 < H_n < H_{D,E}\,, \qquad n = 1, 2, \ldots \tag{6}$$

where $H_0 \approx 60$ *km* is the height of lower boundary of ionosphere, $H_{D,E}$ is the height of upper boundary of D or E-layer, *n* is multiplicity of reflection;

2) as that multiplicity grows the effective heights increase, and thus

$$H_{n+1} > H_n\,; \tag{7}$$

3) as it has to follow from the Fermat principle, every ionospheric wave passes that way which is minimized for the time of passing. Therefore, the true distance r_0 has to conform to minimum positive difference of heights H_{n+1} and H_n , that is

$$\min(H_{n+1} - H_n) > 0. \tag{8}$$

Joining (6)–(8) one can obtain the additional condition to select only that result from a set of solution of the undetermined system (2) which answers the demand

$$\hat{r}_0 = r_0 \Big|_{\min(H_{n+1} - H_n) > 0,\ H_0 < H_{n+1,n} < H_{D,E}}\,, \quad n = 1,2,\ldots \tag{9}$$

Initialisation of the algorithm using (9) is illustrated on Figure 4. It demonstrates some dependencies of delays from distance r_0 and effective reflection heights. The D-layer is considered where these heights are from 60 to 80 *km*. Upper field is conformed with double reflected wave, as lower field illustrates possible delays region for single reflected wave. Finding the values τ_1 and τ_2 from analysis of the atmospherics and setting these values into equation (2) together with mentioned values of heights one can obtain the estimations both minimal $r_{0\,min}$ and maximal $r_{0\,max}$ distances, which correspond to these delays. The difference $r_{0\,max}$ - $r_{0\,min}$ is the range for finding the true value of r_0.

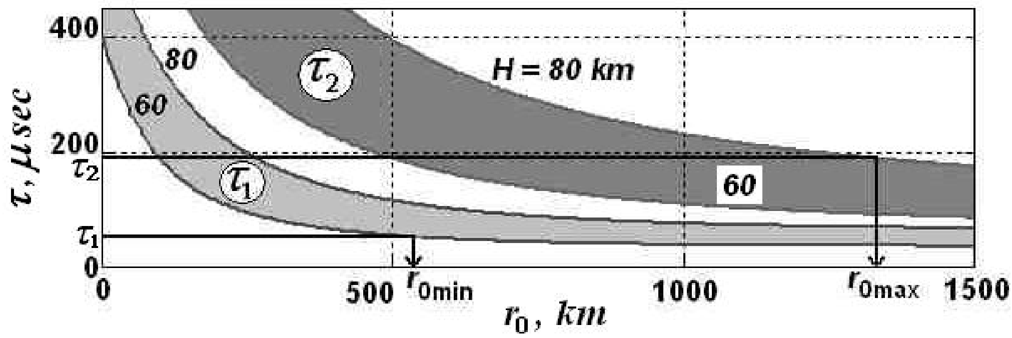

Figure 4. Initial step to start the algorithm (9)

In order to narrow this range the *m*-iteration procedure is introduced as follows.

$m = 1$:

a) Substituting τ_2 and $r_{0\,min}$ into (2) one obtains the new value H_1.
b) By analogy, from τ_1 and $r_{0\,max}$ it is obtained the new value H_2.
c) Then, substituting τ_1 and new H_1 into (2) one obtains the new value $r_{0\,min}$.
d) By analogy, from τ_2 and new H_2 it is obtained the new value $r_{0\,max}$.
e) If $H_2 - H_1 > 0$ and simultaneously $r_{0\,max}$ - $r_{0\,min} > 0$ it has to set $m = m + 1$ and has to repeat these steps from a) to e) and so on.

Stopping criterion is failure of one or both from inequalities in the stage e).

Experiments with this algorithm demonstrate sufficient rate of convergence as it is shown on Figure 5 for the same daytime atmospherics considered before. It is seen the result has been attained during 5 iterations only.

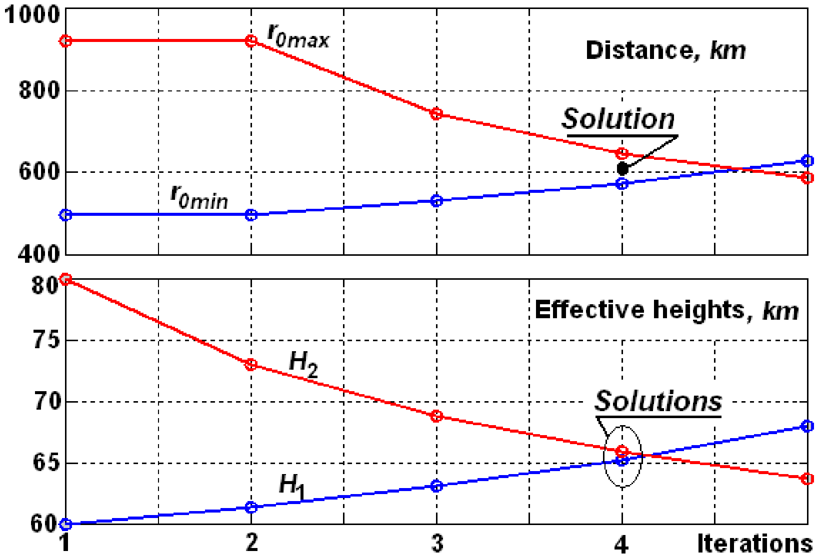

Figure 5. Convergence of the algorithm (9)

As the true value r_0 it is accepted the mean from $r_{0\ max}$ and $r_{0\ min}$ is reached during iteration which is preceded to the stopping. The same iteration determines the solutions of the system (2) for the effective heights H_1 and H_2.

Conclusions

In this research the hop model of propagation of electromagnetic pulse generated by lightning discharge in Earth – ionosphere spherical waveguide is considered. It is ascertained the methods for evaluating of delays of ionospheric waves from atmospherics based on Fourier transformations are non-adequate more often. As an alternative, the pseudocepstral method using Huang-Hilbert transformation is proposed to estimate these delays.

Proceeded from the values of delays, inverse problem concerning geometry of waveguide Earth – ionosphere would be decided with the help of the undetermined system of equations (2). The algorithm of solution eliminating the uncertainties without handling of the data about ionospheric layers parameters is worked out. Both the distance from the lightning discharge and the ionospheric heights can be estimated by a few iterations. It may seem as important contribution to theory of single-station passive location of sources of electromagnetic radiation propagated in ionosphere. All the procedures described above have been realized in Matlab. It is supposed the future works should be devoted to mass processing of atmospherics in order to establish statistic characteristics and precision of that algorithm.

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