XV International Conference on Atmospheric Electricity, 15-20 June 2014, Norman, Oklahoma, U.S.A.

Calculation of the Cloud-to-Ground Lightning Dipole Moment and its Verification Based on Radio ELF Observations and Electric Field Measurements in VLF Range

Zenon Nieckarz*, Andrzej Kułak
Faculty of Physics, Astronomy and Applied Computer Science
Jagiellonian University
ul. Reymonta 4 , 30-059 Kraków, Poland
*Email: zenon.nieckarz@uj.edu.pl

Piotr Baranski, Jan Wiszniowski
Institute of Geophysics
Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warsaw, Poland

Janusz Młynarczyk
Department of Electronics
AGH University of Science and Technology
al. A. Mickiewicza 30, 30-962, Kraków, Poland

Introduction

Many different kind of physical processes are involved in a lightning flash events occurring in the Earth atmosphere at each moment around the world. To describe such complex phenomena we should determine many important parameters related to their persistent and transient nature. One of these parameters can be attainable by an evaluation of the charge moment change (CMC) due to different types of observed lightning flash strokes. There are two way present in the literature how to carry out this indirectly by using relevant measurement technique.

First method was used and described by Krehbiel [1979]. This method is based on multipoint measurements of time changes of the vertical component of electric field strength at the ground (E_z), at four or more sites, during lightning discharge incidents. Here, it is also assumed that a limited spherical and symmetrical volume of electric charge existing in a thundercloud can be removed by a cloud-to-ground (CG) flash and its size is significantly less than the distance from the charge to the measuring point [Krehbiel 1979, Williams 1989]. Taking into account that the value of electrostatic component of E_z decreases rapidly as a function of $1/r^3$, where r denotes the distance from a point electric charge source involved in CG flash, such multi-stations network should be set up by several measuring stations located close to each other, i.e., from a few to tens of kilometres range distance. Although this network has effectively observed a small part of thunderstorm area, only four E-field stations placed at the ground are sufficient to obtain a unique solution of the considered set of four equations and determine four unknown variables, i.e., the coordinates x, y, z of the electric charge center in a local Cartesian coordinate system and charge Q lowered by particular CG stroke to the ground. It is worth noting that z is also the vertical projection of lightning channel CG discharge. The role of redundant E-field measurements at additional sites is to bring more confidence in the searched solutions. Thus, as a final result the searched value of the charge moment change parameter, further called CM_{CVLF}, can be calculated as the product of $Q{\cdot}z$. Similar method was used for charge structure analysis on lightning discharges to the ground by Qie [2000] and for evaluation of multiple ground flash charge structure by Barański [2013].

The second method is based on the measurement of extremely low frequency (ELF) defined as range 3-3000~Hz radiation from the lightning stroke. The charge transfer (Q) and the vertical distance (L) over which that charge is transferred can be considered as a short antenna which emitted the electromagnetic (EM) waves in wide frequency range. The product of ($Q{\cdot}L$) is further called CMC_{ELF}. It can be remotely estimated from ELF measurement [Kulak and Mlynarczyk 2011]. The relationship between CMC_{ELF} and estimated lightning current peak was analysed by Nieckarz et al. [2011] over France as the case study for two thunderstorms. Note that the expression for evaluation of CMC_{ELF} considered in the second method is the same as the one used for calculation of CMC_{VLF} by the first method. We are focused on comparison of CMC values obtained from both methods for finding correlation relationship between CMC_{VLF} and CMC_{ELF}

The multi-site electric field measurements in the VLF range

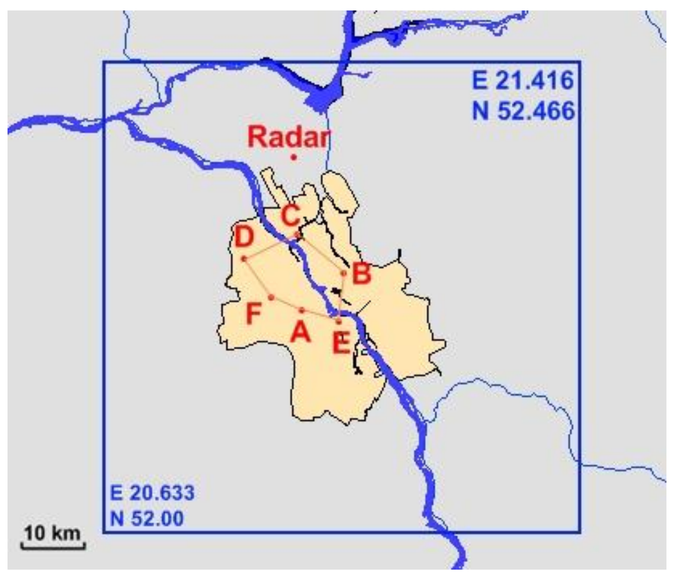

Figure 1. Map of the LLDN network in the Warsaw region (Poland).

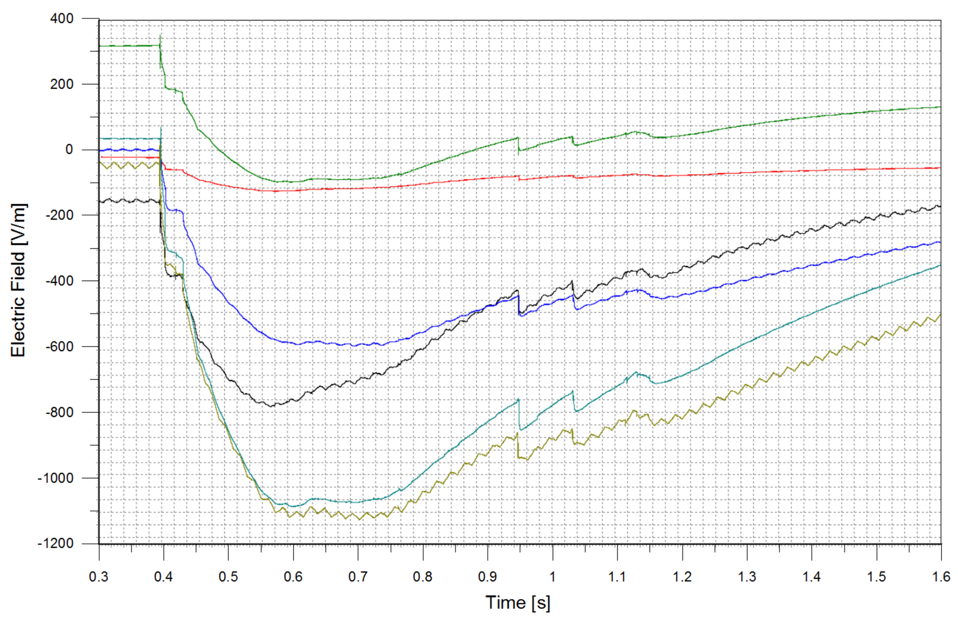

Figure 2. Example of signals registered by the 6 stations.

The VLF signal emitted by different types of lightning discharges was received and collected by six autonomous standing alone stations without any operator assistance required during summer thunderstorm season 2009. These stations called the Local Lightning Detection Network (LLDN). They were set up in the Warsaw region and successfully operated during 2009 measurement field campaign.

Method of calculation of the CMC from the VLF measurements

Having a possibility of multi-site recordings of the (E_z) field associated with CG flash incidents we can obtain relevant field changes (ΔE_{obs}) related to such event and characteristic for the particular LLDN station. These E-field measurements together with the knowledge of the position of each measurement station enable us to calculate three dimensional (3D) location of electric charge and its amount that is transferred from charge point source to the ground during CG lightning stroke. However, we have to disposal six different E-field records while the number of searched unknown parameters equals only four (x, y, z, Q).

Hence, at the beginning we need to use the following expression for describing the analytical relationship between the quantity ΔE_{theor} taken from electrostatic lightning discharge model and set of four searched parameters related also to the fixed 2D location of the particular LLDN station:

$$\Delta E^{i}_{theor}(x,y,z,Q)=\frac{1}{4\pi\cdot\varepsilon_0}\,\frac{2\cdot Q\cdot z}{\left[(x-x_i)^2+(y-y_i)^2+z^2\right]^{3/2}} \qquad (1)$$

In the next step the appropriate numerical method should be used for final finding of the four searched parameters (x, y, z, Q) properly representing the considered lightning CG stroke. This procedure is based on some maximum likelihood probabilistic methods. It should be noted that the best fitting set of these parameters minimizes a Chi-square function given by the following equation:

$$\chi^2=\sum_i \frac{\left[\Delta E_i-\Delta E_i(x,y,z,Q)\right]^2}{\sigma_i^2} \qquad (2)$$

where i - is the standard deviation of the measurement ΔE^i_{obs} due to experimental error. As a result of the above procedure we obtained the electric charge and its coordinates for every flash. Next we calculated charge moment change (CMC_{VLF}) using the following equation:

$$CMC_{VLF}=z\cdot Q \qquad (3)$$

At the end, we have identified the type of every event as a return stroke (RS) or a continuing current (CC). The criterion was the rise time (t_r) of the ΔE-field change signal involved in the considered CMC. If this time was below 3 ms then the flash was identified as the RS, otherwise it was identified as the CC.

The electromagnetic field measurements in the ELF range

Our ELF station is located in a sparsely populated area of the Bieszczady Mountains in Poland (49.19N, 22.55E) in a low electromagnetic noise environment. The station is equipped with two magnetic antennas, east-west and north-south. The signal was recorded by a receiver that has the frequency bandwidth of 0.03 to 52 Hz, the energy bandwidth Δf of 66.1 Hz, and the sampling frequency of 175.96 Hz. The sampling clock is synchronized to Universal Coordinated Time (UTC) using the GPS receiver. View of location of the ELF station and view the main module are shown below.

Figure 4: View of the entry to the ELF station (left) and view of the ELF working station (right).

Method of calculation of the CMC from the ELF measurements

The ELF radio wave propagation in the Earth-ionosphere waveguide is unimodal up to the cutoff frequency for the waveguide (~1500 Hz) and can be accurately modeled [Kulak and Mlynarczyk 2013]. Cloud-to-ground return strokes are fast enough that the recorded signal takes the form of short impulses, which spectrum is flat in frequency range covered by our receiver. This facilitates the use of inverse method for calculation of the source parameters. In this paper we use the method described by [Kułak et al., 2010] and applied to the calculation of the charge moments of ELF pulses associated with terrestrial gamma ray flashes [Kułak et al. 2012]. In this method, the amplitude of an impulse B_{pulse} recorded by a magnetic antenna at the distance r and the charge moment CMC_{ELF} of a return stroke are related by the following equation:

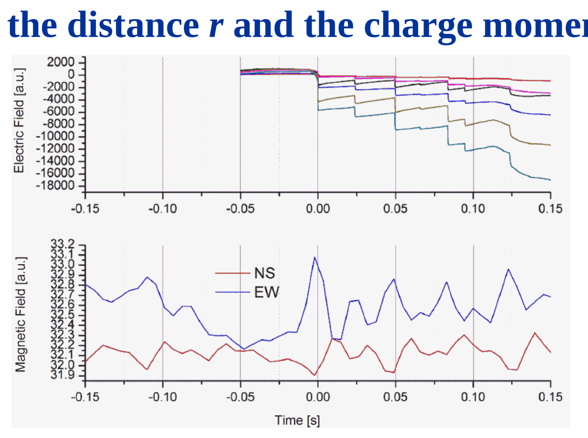

Figure 5: The VLF and ELF signals associated with the same multiple negative CG lightning flash.

From an off-line analysis we knew the VLF time of flash (t_{VLF}) and the total time delay (t_d).

$$t_{ELF}=t_{VLF}+t_d$$

$$B_{pulse}=K(r)\cdot CMC_{ELF} \qquad (4)$$

where $K(r)$ depends on the transfer function of the Earth-ionosphere waveguide $w(r, f)$ and the transfer functions of the receiver $g(f)$. The transfer function of the Earth-ionosphere waveguide depends on the characteristic magnetic altitude of the waveguide $h_{rm}(f)$, the phase velocity $v_{ph}(f)$ and the attenuation rate $\alpha(f)$.

We used the complex altitudes for the daytime ionosphere presented by Kułak et al. [2012], and for the nighttime ionosphere we use the equation described by Kulak and Mlynarczyk [2011]. Once the altitudes are known, the phase velocity and the attenuation rate can be calculated using the complex propagation parameter [Kułak et al. 2013].

Results and conclusions

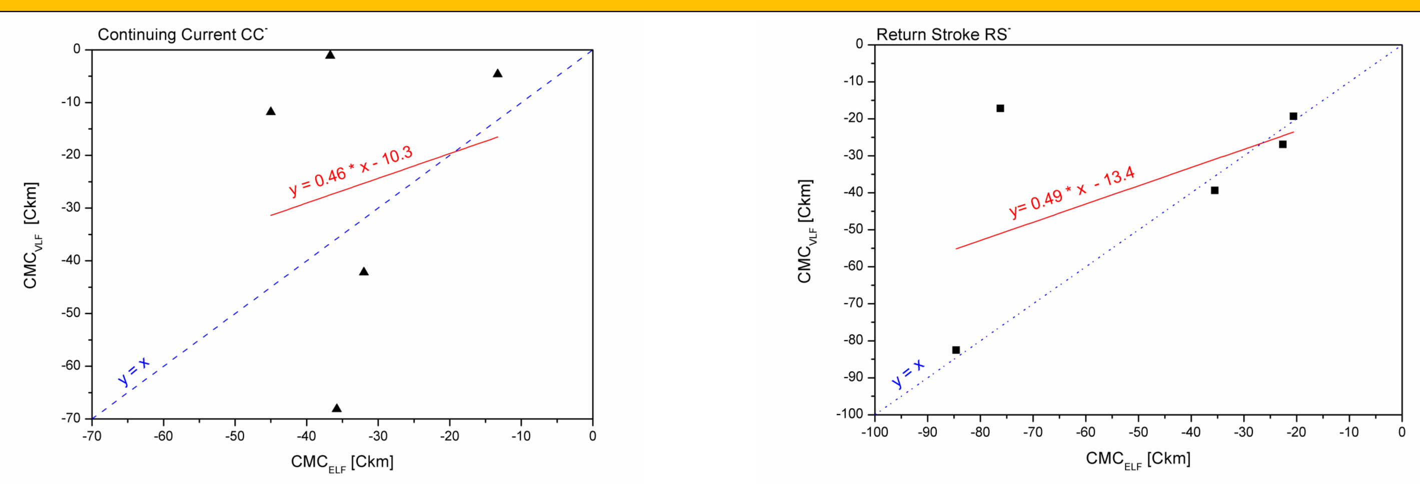

Figure 6. The comparison of the CMC values obtained from VLF and ELF measurements.

Two different kind of independent analysis in VLF and ELF range has been applied to evaluate the relevant CMC value for different CG strokes. Two sets of electric and magnetic data collected by quite variant measurement technique were also taken into consideration. Due to that the final comparison of the obtained CMC_{VLF} and CMC_{ELF} estimations corresponding to the same CG lightning flash has been achieved. The Pearson's coefficient (R) obtained for the assemble of calculated CMC values for CC and RS strokes of the considered CG flashes is equal +0.19 and +0.59 The values of CMC calculated on the base of the VLF method are often underestimated compare to values of CMC calculated using the ELF method. In the Figure~\ref{figure6} this effect is clearly visible. For both types of CG stroke more calculated CMC values are placed above function y=x marked by blue line. This line indicates the ideal relationship that should be exist between both methods and different procedures of the calculation of CMC values.

It is worth noting that the principal and only one criterion, which is used to differentiate RS or CC component of the considered CG flash, is the value of time rise (t_r) of corresponding (ΔE) change. It is possible that such one parameter discrimination is too simplified and did not always distinguish properly the considered lightning stroke events.

Acknowledgments

This work is supported by grant number NCN-2011/01/B/ST10/06954, National Science Centre, Poland.

References

Barński, P., M. Loboda, J.Wiszniowski, and M. Morawski, Evaluation of multiple ground flash charge structure from electric field measurements using the local lightning detection network in the region of Warsaw, Atmos. Res., 117, 99–110, 2013.
Krehbiel, P. R., M. Brook, and R. A. McCrory, An analysis of the charge structure of lightning discharges to ground., J. Geophys. Res., 84, 2432–2456, 1979.
Kulak, A., and J. Mlynarczyk, A new technique for reconstruction of the current moment waveform related to a gigantic jet from the magnetic field component recorded by an elf station, Radio Sci., 46, 2011.
Kulak, A., and J. Mlynarczyk, ELF propagation parameters for the ground-ionosphere waveguide with finite ground conductivity., IEEE Transactions on Antennas and Propagation, 61, 22692275, 2013.
Kułak, A., Z. Nieckarz, and S. Zięba, Analytical description of ELF transients producing by cloud-to-ground lightning discharges, J. Geophys. Res., 115, 2010.
Kułak, A., J. Młynarczyk, M. Ostrowski, J. Kubisz, and A. Michalec, Analysis of ELF electromagnetic field pulses recorded by the Hylaty station coinciding with terrestrial gamma-ray flashes, J. Geophys. Res., 117, 2012.
Kułak, A., J. Młynarczyk, and J. Kozakiewicz, An analytical model of elf radiowave propagation in ground- ionosphere aveguides with a multilayered ground, IEEE Transactions on Antennas and Propagation, 61, 4803–4809, 2013.
Nieckarz, Z., A. Kułak, S. Zieba, and A. Odzimek, Cloud–to–ground lightning dipole moment from simultaneous observations by ELF receiver and combined direction finding and time of arrival lightning detection system, J. Geophys. Res., 116, 2011.
Qie, X., Y. Yu, X. Liu, C. Guo, D. Wang, T. Watanabe, and T. Ushio, Charge analysis on lightning discharges to the ground in Chinese inland plateau (close to Tibet), Ann. Geophysicae, 18, 1340–1348, 2000.
Williams, E., The tripole structure of thunderstorms, J. Geophys. Res., 94, 13,15113,167, 1989.