Calculation of the cloud-to-ground lightning dipole moment and its verification based on radio ELF observations and electric field measurements in VLF range

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ABSTRACT:

We present two methods for the charge moment change (CMC) calculation that is connected with the cloud-to-ground lightning discharges. The first method uses multi-station ground-based measurements of lightning-generated electric field variations for the purpose of the lightning flash location and charge analysis. Our 6 stations were called the Local Lightning Detection Network (LLDN), and set up in the Warsaw region. The second method is based on the one station measurements of the horizontal magnetic component of the ELF waves generated by atmospheric discharges. Our ELF station is equipped with two magnetic antennas, east-west and north-south and is located in a sparsely populated area of the Bieszczady Mountains in Poland (49.19N, 22.55E). There are presented and discussed the results achieved by the both methods, focusing especially on the negative return stroke (RS) and continuing current (CC) lightning discharges. Results show that the correlation between the CMC obtained by the two methods for negative CC and RS is equal to +0.19 and +0.59, respectively.

INTRODUCTION

Direct measurement of many physical phenomena which are necessary to precision describing of lightning is impossible. One of these parameters is charge moment change (CMC). In the literature described two methods to intermediate measure this parameter.

First method was used and described by Krehbiel et al. [1979]. This method is based on multipoint measurement vertical component of an electrical field strength (E_z) during lightning discharge and in this method is assumed the aspheric symmetric of electric charge in the cloud and its size is significantly less than the distance from the charge to the measuring point [Krehbiel 1986; Williams 1989]. Such a network is measuring points located close to each other (from few to tens kilometres) because the electric field surrounding a charge decreases rapidly with distance. Finally the network effectively observed a small area. As a result is obtained information about location (*x*,*y*,*z* ; note that *z* is also the vertical projection of channel discharge) of an electric charge (*Q*), which is neutralized in cloud to ground discharge and its

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value and sign. Using this parameter the charge moment change (called CMC_{VLF} as product $Q{\cdot}z$) can be calculated. This method was used for charge structure analysis on lightning discharges to the ground [Qie et al. 2000] and to evaluation of multiple ground flash charge structure [Barański et al. 2012].

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 are a short antenna which emitted the EM waves in wide rage. The product of $Q{\cdot}L$ is called CMC_{ELF}. It can be remotely estimated from measurement of ELF [Jones and Kemp, 1971; Burke and Jones, 1996; Huang et al., 1999; Cummer and Inan, 2000; Hobara et al., 2001, Kułak et al. 2010]. The relationship between CMC and peak current was analysed by Nieckarz et al. [2011] over France as case study (two storms) and next by Cummer et al. [2013] over the United State with great statistic (3 years of measurements).

Note that the product of charge transfer and vertical channel length of discharge are the same CMC like in the first method. Here we compare CMC values obtained from both methods for testing relationship between CMC_{VLF} and CMC_{ELF} and particular testing propagation formulas used for ELF range [Kułak et al. 2010, Kułak et al. 2012]. It is first verification of CMC measurements based on two different methods.

The multisite electric field measurements in the VLF range

The VLF signal was collected by six autonomous standing alone stations without any operator assistance required during summer thunderstorm season 2009. These stations were called the Local Lightning Detection Network (LLDN), were set up in the Warsaw region and successfully operated. Each site of installation was chosen as a compromise of the absence of high conductive elements, power lines or buildings in the close neighbourhood, easy accessibility and low cost of adaptation. The location of each station (A, B, C, D, E, F) is shown in Figure 2, while a picture of the A station situated on roof of the Warsaw University of Technology building is showed in Figure 1. Station D located in a flat and open area of Warsaw-Babice aerodrome has been assigned as a "reference station". In detail, the process of site selection and calibration was described in (Baranski 2012).

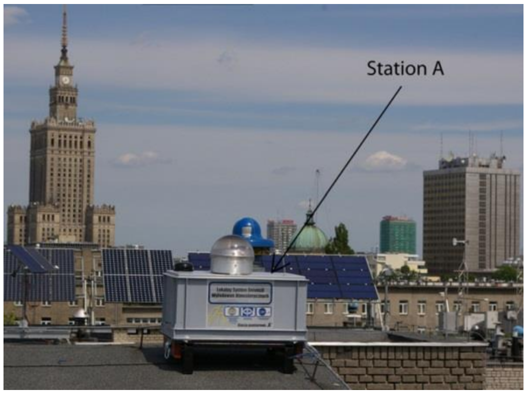

Figure 1 View of location of the station A in the center of Warsaw.

Figure 2 Map of the LLDN network

The main parts of each station are the E-field antenna with preamplifier, the GPS receiver with antenna and the recording device which was build based on the standard PC/104 built-in computer. The internal hard disk (~150 GB data buffer) allows temporary storage of registered data for at least 3 days (72-hour continuous registration). Functional block diagram of the whole station is depicted in Figure 3.

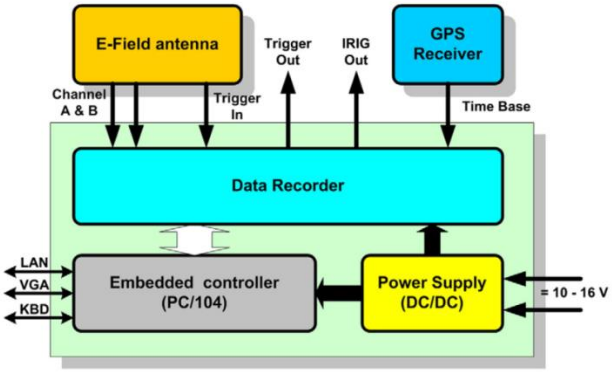

Figure 3 Block diagram of the VLF station

The functionality of recording device includes A/D signal conversion (14 bits, 40 MHz) with antialiasing low-pass filter (bandwidth 100 kHz), digital signal processing, and data sample buffering in the internal memory. The recorder control logic provides precise data sample time synchronization to the Universal Coordinated Time (UTC). The GPS receiver provided pulse per second output (1 PPS) as a reference source for data sample time tagging (with an accuracy of +/-1 μs).

Every station working independently and controls its own signal Trigger In (STI) coming from E-Field antenna. If the STI crossing a threshold level then the time interval 2.5 s (with additional 100 ms pre-trigger data) of the digital stream of data are archived. If during this interval the STI crossing again the threshold level then the recording stream time was extended by next 2.5 s.

During summer season in 2009 many cases of different types of cloud-to-ground (CG positive and negative) lightning flash detections were collected in database. For next step of analysis we extracted only these cases when all six stations recorded field changes (ΔE) caused by the same flash with negative polarity and finally we found 49 that cases. In every time interval of cases contains one or more field changes (single or multiple flashes). A sample of graph of that registration is presented in

Figure 4 where we can see few field changes from flashes during time interval of one case.

Method of calculation of the charge moment change from the VLF

Having a multisite registrations of *E* field (the vertical component) we calculate field changes (ΔE_{obs}) for every six location. This information, together with the knowledge of the position measurement stations gave the possibility to calculating three dimensional locations and an amount charge of electric charge that flowed during a discharge. At the end we have six observations while the number of estimated value equals four (x, y, z, Q). Equation 1) describes analytical relationship between ΔE_{theor} and the four searched parameters.

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

Equation 1

Where *i* indicate name of station; ε_0 is the vacuum permittivity; x_i, y_i, z_i are coordinate of the *i*-th station in the local Cartesian system.

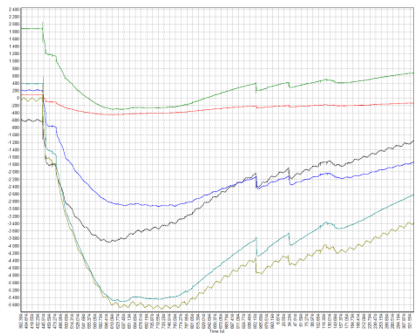

Figure 4 Example of signals registration in 6 stations

The numerical method used for finding the four searched parameters (*x*, *y*, *z*, *Q*), of a particular lightning stroke is based on the maximum likelihood method. These parameters minimize a Chi-square function given by the

Equation 2.

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

Equation 2

Where σ_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 flashe. Next we calculated charge moment change (CMC_{VLF}) using

Equation 3.

$$CMC_{VLF} = z \cdot Q$$

Equation 3

At the end, we have identified type of every event as return stroke (RS) or continues current (CC). The criterion was rise time (t_r) of signal after *CMC*. If this time was below 3 ms then flash was identified as the RS else was the CC type.

The one station magnetic waves measurements in the ELF range

The 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.

Method of calculation of the charge moment change 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 [Kułak and Młynarczyk 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 in Kulak 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 to by the equation

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

Equation 4

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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)*:

$$K(r) = \sqrt{\frac{\pi\ \Delta f}{\chi} \int_0^\infty \left| w(f,r) \cdot g(f) \right|^2 df}$$

Equation 5

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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 $\alpha(f)$ through the relationship (Equation 6):

$$w(r,f) = -i \frac{\pi\ \mu_0 f}{2h_{rm}(f) v_{ph}(f)} H_1^{(2)}\left(2\pi\ r \frac{f}{v_{ph}(f)}\right) e^{-\alpha(f) r}$$

Equation 6

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where μ_0 is the permeability of free space, H_1^2 is the Hankel function of the second kind and first order. In this study we use the complex altitudes for the daytime ionosphere presented by Kułak et al. [2012], and for the nighttime ionosphere we use the equation described in Kułak and Młynarczyk [2011]. Once the altitudes are known, the phase velocity and the attenuation rate can be calculated using the complex propagation parameter [Kulak et al. 2013].

The delay of the recorded signal results from the group delay in the Earth-ionosphere waveguide and the signal delay in the receiver. Both delays can be calculated from the respective transfer functions. Since the signal takes the form of short impulses, the group delay is derived using the velocity of high frequency components forming the vertex of the impulse. The average distance between centre of the LLDN stations and the ELF station is 350±6 km. So the propagation delay in the analysed cases was equal to 1.3 ms for the nighttime paths and 1.5 ms for the daytime paths. The receiver's group delay is equal to 15.0 ms. We assumed that the total time delay (t_d) equals 16.5 ms for all flashes.

We analyzed the ELF signals associated with the lightning discharges registered by the LLDN network in the VLF bandwidth. In off-line analysis we know the VLF time of flash (t_{VLF}) and the total time delay (t_d) then we calculated the time of the impulse in the ELF signal using Equation 7.

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

Equation 7

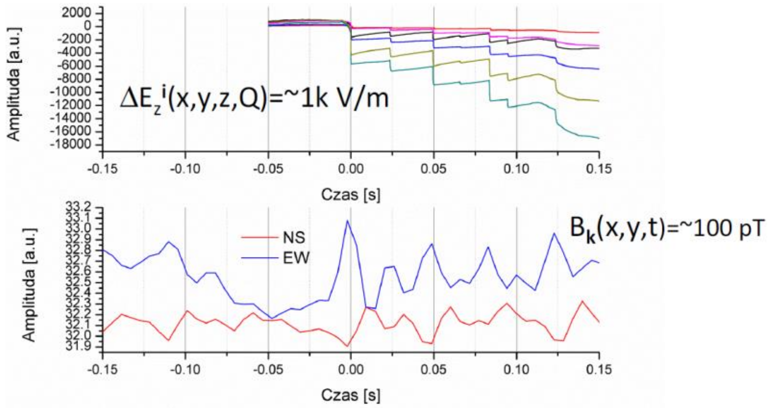

Figure 5 Time of VLF i ELF flashes.

The calculation of time correction was verified based on multi flashes events. Figure 5 shows an example of such verification. It is clear visible that for every greater E-field changes exist pulse of magnetic field in the ELF station. Unfortunately not all flashes cases registered in the LLDN network could be used to calculate the charge moment (CMC_{ELF}). Because the method described above can be used for impulses with relatively constant background then only 26 cases from all 49 cases registered by the VLF network was analyzed.

RESULTS AND DISCUSION

Both types of measurement and analysis deliver and finally we compare values of the *CMC* obtained from two completely different and independent method. In the Figure 1 is scatter plot of CMC_{VLF} versus CMC_{ELF} for the CC (top, 16 samples) and the RS (bottom, 10 samples) flashes.

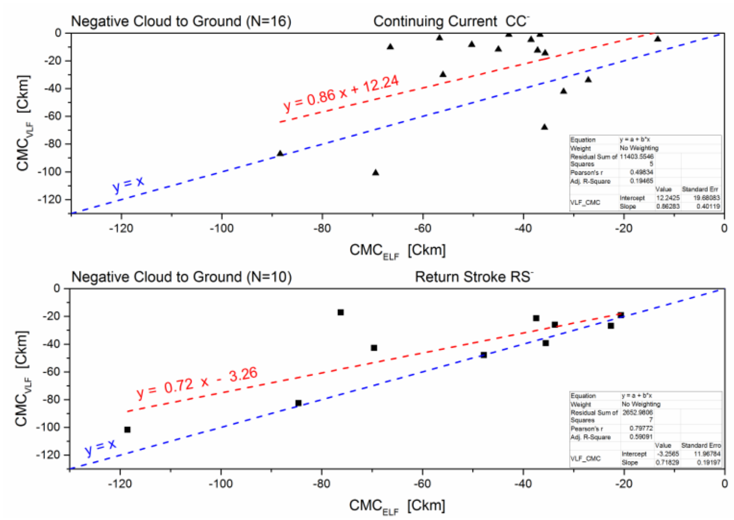

Figure 6 The comparison of the *CMC* values obtained from VLF and ELF measurements.

The Pearson's coefficient (*R*) for CC and RS types of flashes is equal 0.50 (p=0.049) and 0.80 (p=0.0057) respectively while the coefficient of determination (R^2) equal 0.19 and 0.59 respectively. We also examined these two groups of data using paired sample t-Test. For the CC pairs (CMC_{VLF}, CMC_{ELF}), at the p=0.05 level, the difference of the population means is significantly different while for the RS pairs this difference is not. The values of CMC calculated based on the VLF method are often underestimates compare to value CMC calculated using the ELF method. In the Figure 6 this effect is clear visible. In both types of discharges more points are above function $y=x$ marked by blue line. This line indicates ideal relations between both methods calculated the CMC. It should be noted that the main (and only one) criterion, which is used to divide lightning discharges for CC and RS flashes, was time rise (t_r). It is possible that this method is too simple and not always properly separates these discharges.

CONCLUSIONS

Presented in this paper results show relationship between change moment charges obtained from two independent method. One is based on electrostatic law and measurement E_z in the VLF band close location of lightning, second is based on electromagnetic propagation law and measurement of magnetic component at distance 350 km in the ELF band. The difference of the population means between CMC_{VLC} and CMC_{ELF} is not significant only for the RS negative cloud to ground discharges at the p=0.05 level. The VLF method often underestimates the CMC values than the ELF method. The propagation formulas (Equations 1 etc.) used in this paper in ELF method are correct.

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