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Electric Structure of Multiple Cloud-to-Ground Flashes Obtained from the Local Lightning Detection Network Recordings During Thunderstorm in the Warsaw Region on 25 May 2018

Piotr BARAŃSKI[1,✉]
[1]Institute of Geophysics Polish Academy of Sciences, Warsaw, Poland

✉ baranski@igf.edu.pl

1. INTRODUCTION

The occurrence of multiple Cloud-to-Ground (CG) flash incident is a manifestation of the complex electric charge space configuration existing in the bottom layer of a thundercloud. Thus, if we are able to evaluate the 3D location and the amount of the electric charge Q, involved in the particular component of this lightning discharge, i.e., the return stroke or the continuing current stage, from our multi-station E-field recordings on the ground (at least in four distant locations), then it is possible to have an insight into how such electric structure of the particular thundercloud region favorable for lightning initiation is built. Sometimes these multiple CG flashes are grouped in repeated episodes in short time intervals, e. g., from a few to several minutes, what can inform us about the time changes of the electric charge space redistribution in this thundercloud region. More detail and general information on multiple CG flashes is given for example in Table 1.1 in Rakov and Uman (2003, Ch. 1, p. 7).

2. MEASUREMENT SET-UP AND RESULTS

The four Local Lightning Detection Network (LLDN) stations were located at different and distant places in the Warsaw region and were used to record the E-field signatures of lightning discharges during the field thunderstorm measurement campaign in 2018. This network configuration is shown in Fig. 1, and the exemplary general view of one LLDN station is given in Fig. 2. Using only four of the LLDN stations we were able to find the four searched parameters, i.e., three space coordinates x, y, z and the electric charge Q involved in the particular lightning stroke. However, we cannot assess the errors of such particular solution. In order to do error evaluation we should use more than four LLDN stations for our E-field recordings and this was impossible for us in the 2018 season campaign. The full error analysis of the best search solution in the case when we have to disposal six LLDN stations located at different places in the Warsaw region is given by Baranski *et al.* (2011). This paper also contains more detailed description of our LLDN recording system performance and its calibration.

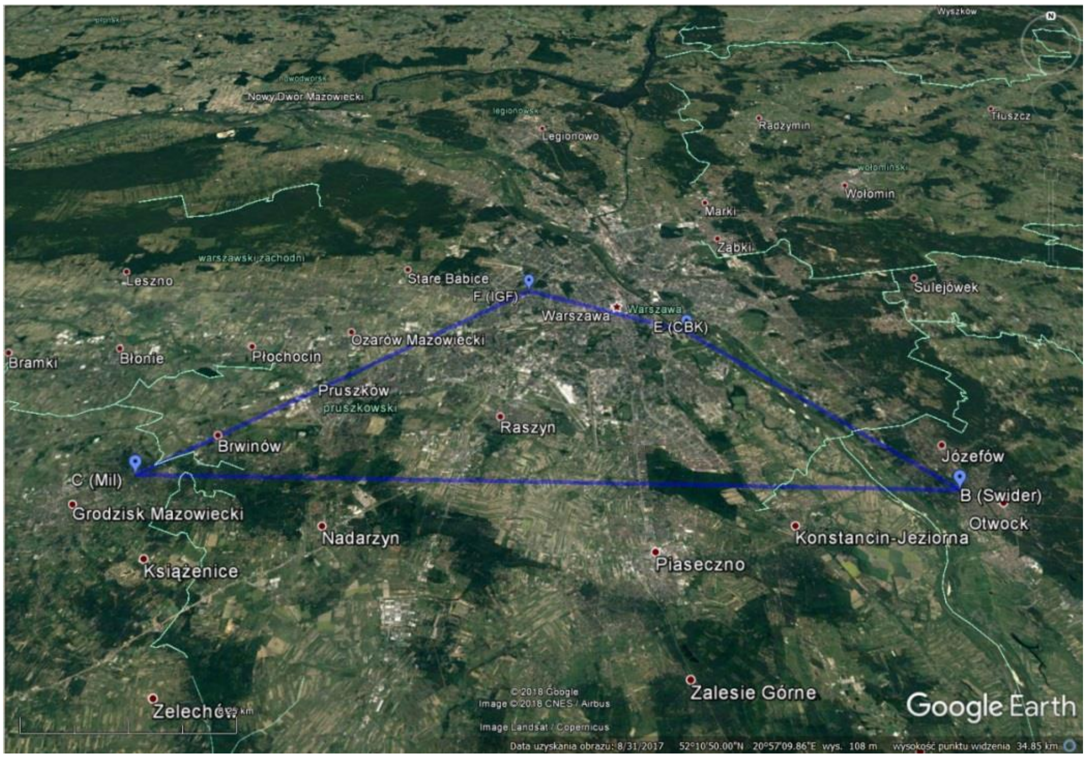

Fig. 1. The locations of four LLDN stations in the Warsaw region during field thunderstorm measurement campaign in 2018. The distances between particular LLDN stations are: LLDN-C(Milanówek) – LLDN-F(IGF) 23 km, LLDN-F(IGF) – LLDN-E(CBK) 9.4 km, LLDN-E(CBK) – LLDN-B(Świder) 16 km, LLDN-C(Milanówek) – LLDN-B(Świder) 39.1 km. Satellite map from Google Earth.

Fig. 2. The general view of LLDN-F(IGF) station located at the roof of IG PAS building. The GPS Garmin receiver and E-field antenna sensor mounted on the top of the grey box with the A/D recorder and the power supply buffer inside.

The selected three exemplary incidents of multiple CG flashes retrieved from the thunderstorm episode in the Warsaw region on 25 May 2018 are given in Figs. 3a–3c.

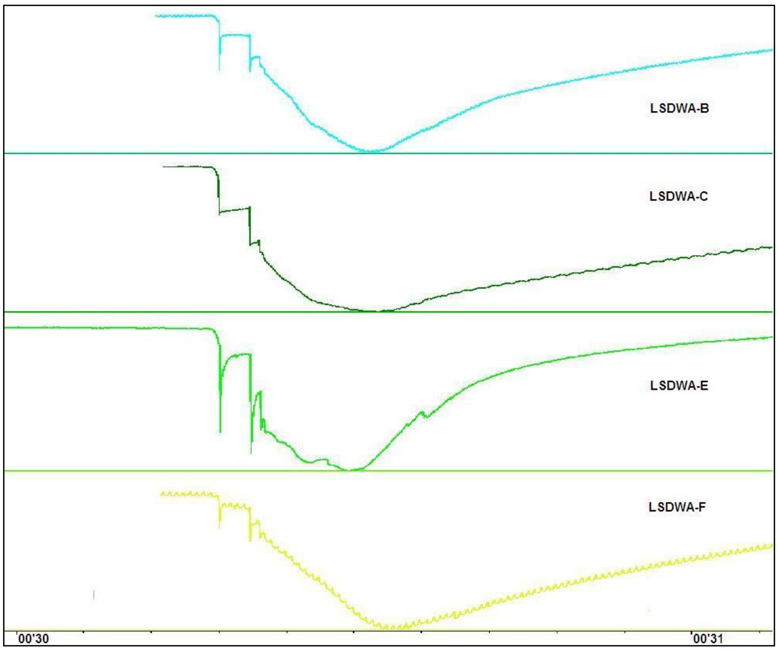

Fig. 3a. The E-field signatures of a multiple negative CG flash simultaneously recorded by four LLDN stations. This CG flash was recorded at 11:00:30 UT and consisted of three return strokes ending with continuing current stage, and lasted 0.21 s.

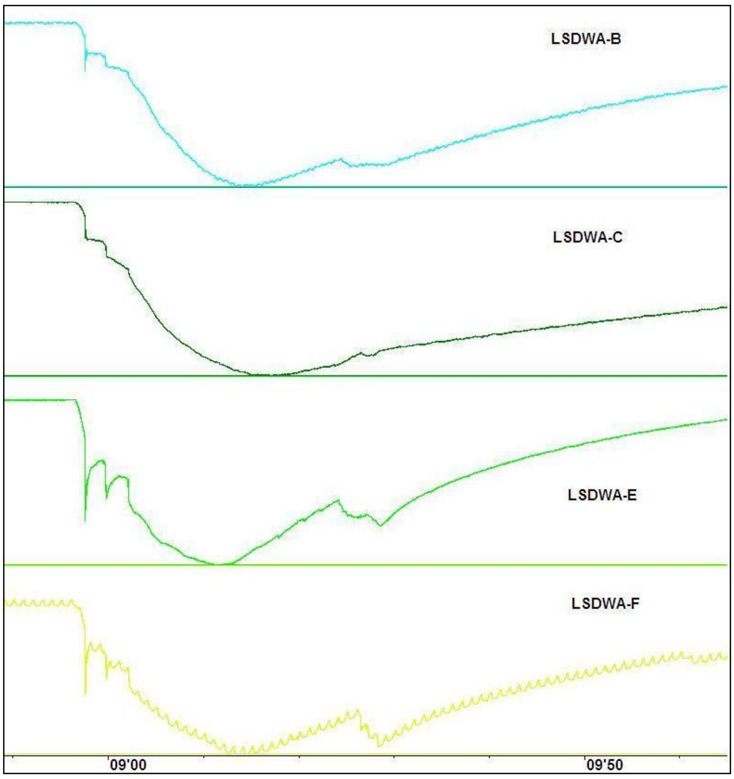

Fig. 3b. The same as in Fig. 3a, except the time occurrence at 11:03:08 UT. This multiple CG flash lasted 0.25 s.

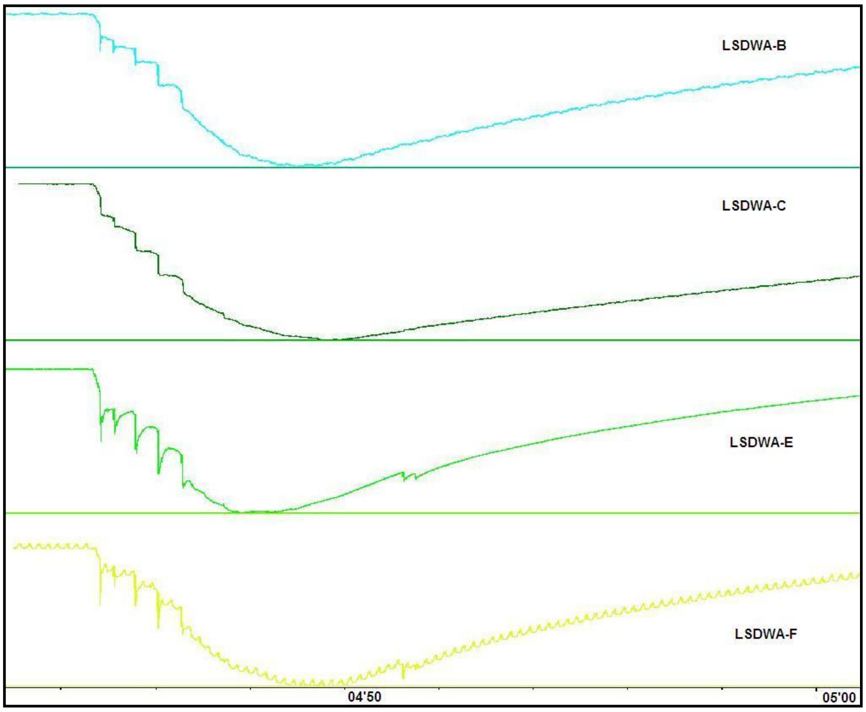

Fig. 3c. The same as in Fig. 3a, except the time occurrence at 11:04:04 UT and the flash multiplicity. This multiple CG flash consisted of five return strokes also ending with continuing current stage, also lasted 0.25 s.

The thunderstorm episode in the Warsaw region on 25 May 2018 was characterized by significant and frequent initiations of multiple CG flashes. During the time interval from 11:00:30 to 11:14:15 UT the LLDN stations detected 11 such CG flash incidents (see Table 1).

The 3D location and electric charge amount of lightning stroke sources for the three considered multiple CG flashes during the thunderstorm episode in the Warsaw region 25 May 2018 are presented in Figs. 4a–4c.

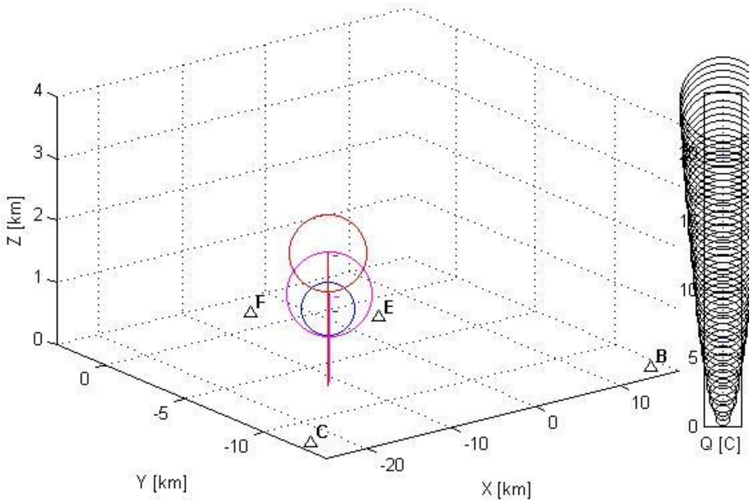

Fig. 4a. The (x, y, z, Q) parameters for three return strokes involved in the multiple CG flash recorded at 11:00:30 UT; the first stroke indicated by red color, the second by magenta color, and the third one by blue color. These strokes discharged the total electric charge of -51.5 C in the thundercloud. The small triangle with big letter B, C, E, and F indicates the plane location of the particular LLDN station.

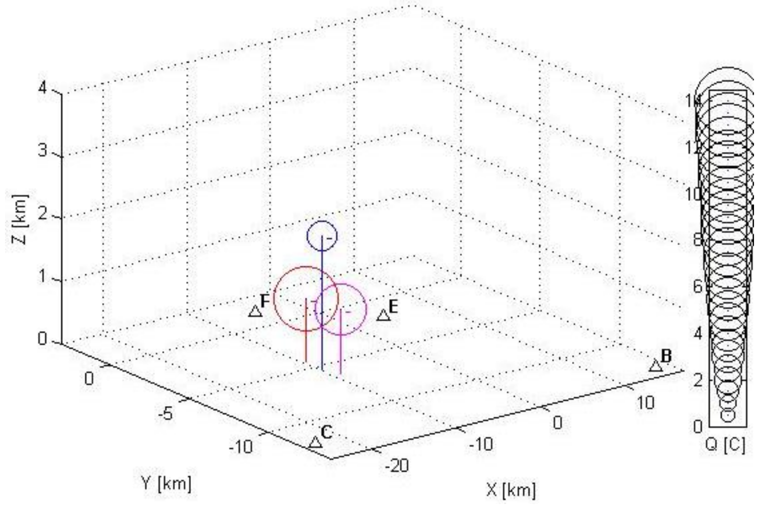

Fig. 4b. The same as in Fig. 4a, except the time occurrence of the multiple CG flash at 11:03:08 UT. Here, the three strokes discharged the total electric charge in the thundercloud equal to -24.7 C.

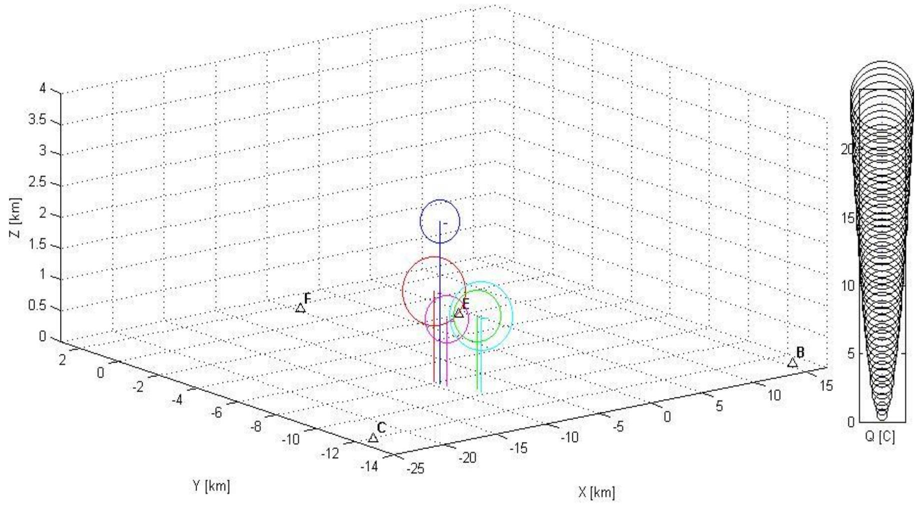

Fig. 4c. The same as in Fig. 4a, except the time occurrence at 11:04:04 UT and multiplicity of this CG flash. It consists from 5 return strokes. The first stroke is indicated by red color, the second by magenta color, the third by blue color, the fourth by cyan color, and the fifth one by green color. Here, these five strokes discharged the total electric charge in the thundercloud equal to -79.2 C.

Having the (x, y, z) parameters for each charge source that was involved in the particular return stroke of the considered multiple CG flashes we can overlap them on the relevant in time PCAPPI/plane return stroke positions and VCUT/vertical return stroke positions radar maps. In this way we can distinguish such thundercloud regions where there were favorable conditions for the development/initiation of the considered multiple CG flashes. These superpositions are shown below in Figs.5a–5c and Figs.6a–6c, respectively.

It is worth noting that all electric charge source locations of the considered return strokes involved in multiple CG flashes overlapped on the PCAPPI and VCUT radar maps (see Figs. 5a–5c and Figs. 6a–6c) are collocated with the intense core of precipitation shaft at the base of the thundercloud. It could mean that the large amount of negative electric charge in this thundercloud layer is deposited on big highly charged cloud particles that later on are giving gush rain at the ground. The most frequent occurrence of multiple CG flashes was recorded

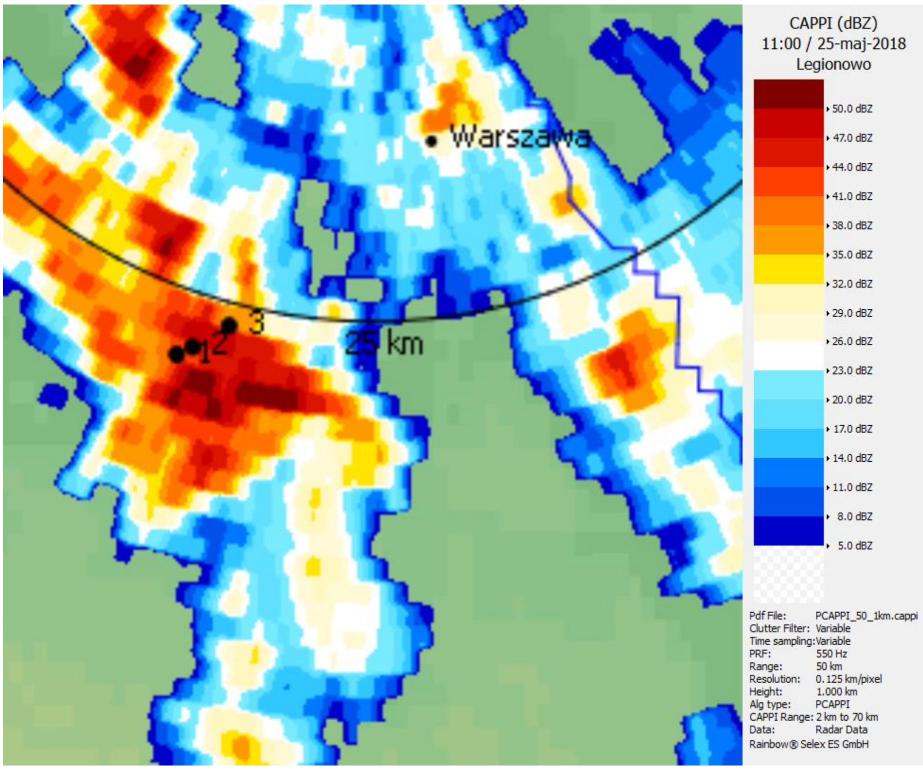

Fig. 5a. The plain locations of three return strokes from the multiple CG flash recorded at 11:00:30 UT and overlapped on the PCAPPI radar map from 11:00 UT. Here, radar data are taken from the meteorological radar (METEOR 1500C) at Legionowo station and operated by the IMWM-NRI.

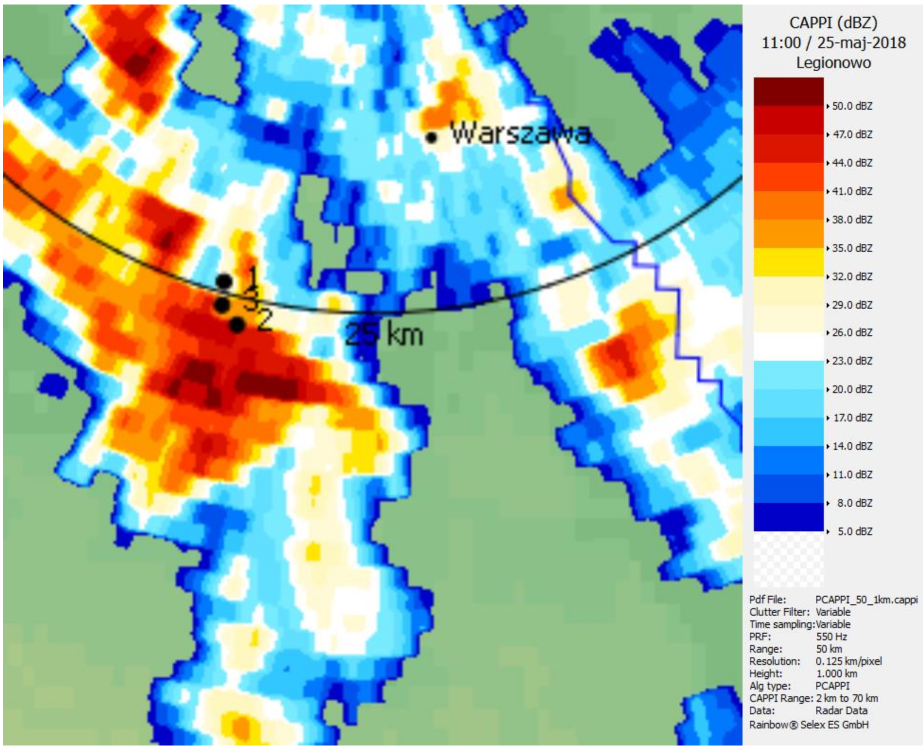

Fig. 5b. The same as in Fig. 5a, except the time occurrence of multiple CG flash at 11:03:08 UT.

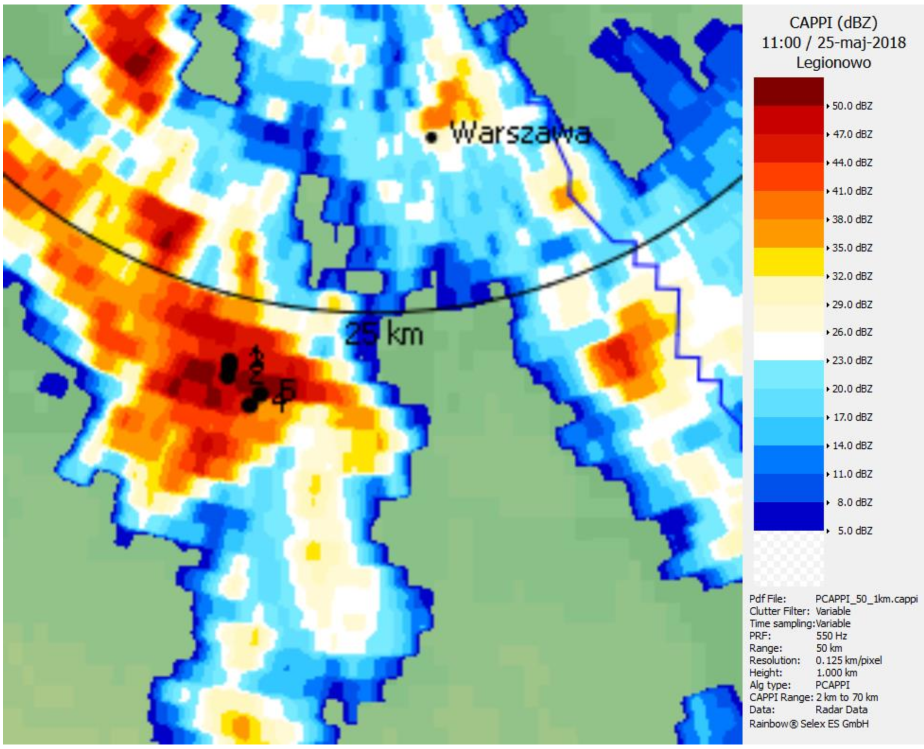

Fig. 5c. The same as in Fig. 5a, except the time occurrence at 11:04:04 UT and multiplicity of this CG flash.

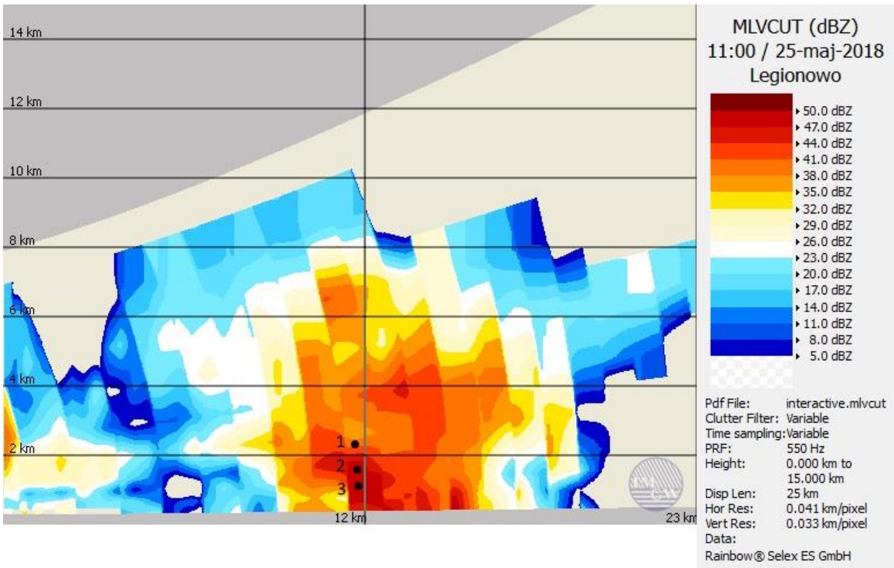

Fig. 6a. The height of the particular return stroke electric charge source of multiple CG flash recorded at 11:00:30 UT and overlapped on the VCUT radar map from 11:00 UT. Here, this height is equal to 1.5, 1.1 and 1.2 km, respectively. The radar data are taken from the meteorological radar (METEOR 1500C) at Legionowo station and operated by the IMWM-NRI.

during the thundercloud dissipation stage and lasted from 11:00 to 11:15 UT. In this time period we were able to distinguish eleven such lightning discharge incidents using our LLDN data in the post-time analysis. These CG flashes are listed together in Tab. 1. It is worth noting that

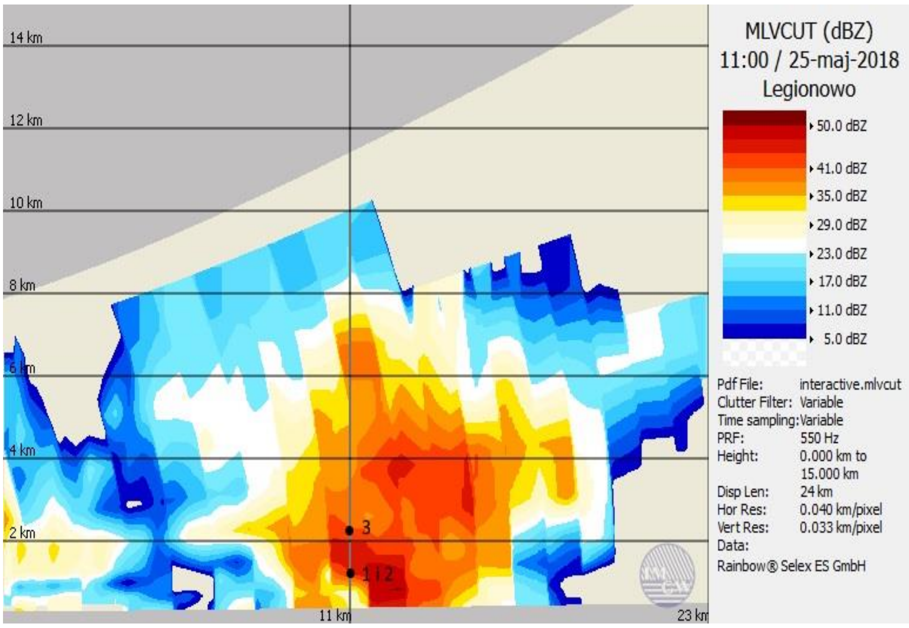

Fig. 6b. The same as in Fig. 6a, except the time occurrence of multiple CG flash at 11:03:08 UT and with the height of stroke sources at 1.0, 1.0 and 2.1 km, respectively.

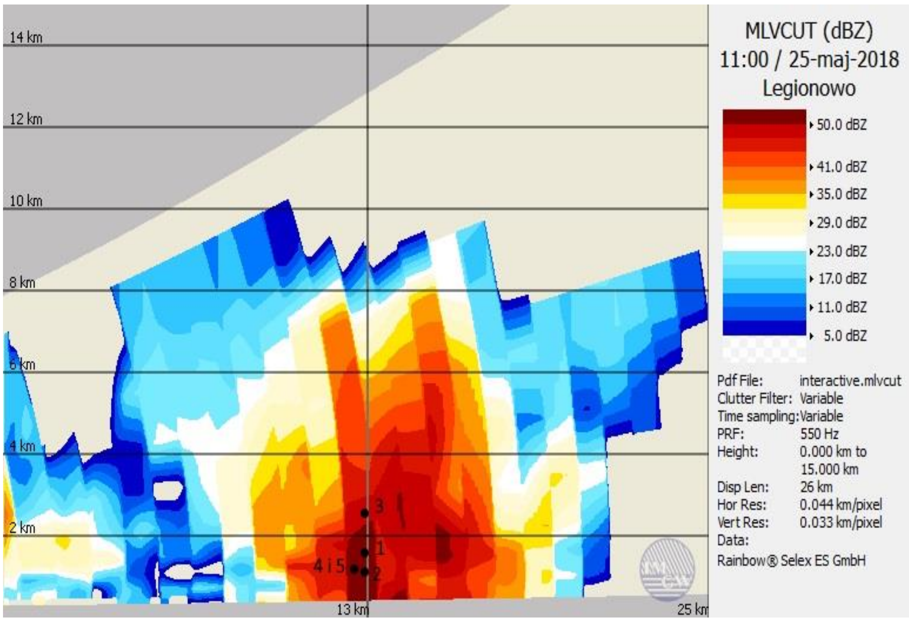

Fig. 6c. The same as in Fig. 6a, except the time occurrence at 11:04:04 UT and multiplicity of this CG flash. Here, the height of stroke sources is equal 1.5, 1.1, 2.6, 1.2 and 1.2 km, respectively.

although we had not possibility of using the fifth redundant LLDN station allowing us for calculation of errors of the searched quantities (x, y, z and Q), we can in the end, make a coarse assumption that for each return stroke we find its plane location as an independent observation that should indicate similar plane coordinates, i.e., x and y for successive impacts in a multiple CG discharge. Such a coarse assumption can of course not be extended to its z and Q component. But, analysing the values of Δd given in Tab. 1, we can note that for the majority of cases obtained the results are satisfactory and Δd is less than a few km.

Table 1

The general characteristic of eleven multiple CG flash incidents distinguished from the LLDN data during thunderstorm in the Warsaw region on 25 May 2018

No. multiple CG flash (order and type of its strokes); time of occurrence of .dat file [UT]	Time interval between subsequent strokes [ms]	Δd [km]	Δz [km]	Q_{total} [C]	Range of χ^2
#1(1RS-,2RS-, 3RS&CC-); 11:00:30	45.2;15	2.6	1.1	-51.5	5.4÷8.3
#2(1RS-,2RS-, 3RS&CC-); 11:03:08	22;24	1.5	1.1	-24.7	2.9÷7.2
#3(1RS-,2RS-,3RS-,4RS,5RS&CC); 11:04:04	14.4;22.4;24;26	1.9	1.5	-79.2	0.35÷3 .5
#4(1RS-,2RS&CC-); 11:08:19	19.2	0.6	0.6	-30.7	5.8÷9.3
#5(1RS-,2RS-); 11:12:05	28	2.7	0.8	-27.3	0.003÷0.04
#6(1RS-,2RS&CC-); 11:12:05	18	14.3	0.1	-24.1	0.07÷16.3
#7(1RS-,2RS-); 11:12:57	40	8.2	0.8	-40.5	0.004÷0.11
#8(1RS-,2RS-,3RS-,4RS-); 11:12:57	28;44;48	15.3	3.1	-36.4	0.007÷0.44
#9(1RS-,2RS-); 11:12:57	56.5	4.1	5.0	-20.3	0.002÷0.1
#10(1RS-,2RS-,3RS-); 11:14:15	16;22	10.2	0.9	-30.8	0.04÷4.4
#11(1RS-,2RS-,3RS,4RS,5RS); 11:14:15	42;44;88;72	16.9	3.0	-80.6	0.03÷0 .11

The maximal and minimal value of the particular parameter is marked by blue and green color, respectively. The abbreviation RS stands for return stroke, the CC stands for continuing current, Δd denoted horizontal extent of multiple CG flash and Δz denotes its vertical extent. The range of χ^2 value determines the best fit for the found particular location of return stroke electric charge source from four different optimization procedures, i.e., the accurate grid search procedure, the downhill simplex procedure and two kind of the annealing procedures, using in the post-time analysis of our LLDN data. The relevant literature references of used optimization procedures are given in Baranski *et al.* (2011).

3. CONCLUSIONS AND FINAL REMARKS

The lightning data delivered by the LLDN can be used in the post-time processing to reliable evaluation of the electric structure of multiple CG flashes by giving their important stroke parameters, i.e., the exact time occurrence up to 1 μs, 3D location and the amount of electric charge discharged by the particular stroke. On the other hand, the E-field signatures of such flashes that are recorded in the radio VLF range and are archived in the recorder memory buffer and are covering all time development of the considered CG lightning discharges, i.e., from the early preliminary breakdown, the stepped leader stage and the return stroke sequence with ending continuing current phase. Such comprehensive presentation and documentation of these CG lightning events cannot be obtained from any lightning location systems routinely operated in large scale in Poland, e.g., the Polish PERUN or the German LINET system.

It is worth noting that the LLDN lightning data superimposed in the same time on the PCAPPI and VCUT radar maps can indicate these thundercloud regions that are favorable for initiation of multiple CG flashes.

Any kind of supplementary lightning data connected with initiation of multiple CG flashes are very desired to ensure relevant lightning protection of the urban high rise buildings, especially in the Warsaw region.

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STRUKTURA ELEKTRYCZNA DOZIEMNYCH WYŁADOWAŃ WIELOKROTNYCH NA PODSTAWIE ICH DETEKCJI W SIECI POMIAROWEJ LSDWA W REJONIE WARSZAWY PODCZAS BURZY 25-05-2018 R.

Streszczenie

W pracy przedstawiono wyniki lokalizacji przestrzennej (we współrzędnych lokalnego i prostokątnego układu kartezjańskiego: x, y, z) oraz polarność i ładunek elektryczny wszystkich źródeł w chmurze burzowej, rozładowywanych przez poszczególne udary piorunowe w czasie wybranych wielokrotnych wyładowań doziemnych podczas burzy w rejonie Warszawy 25-05-2018 . Zmiany pola elektrycznego tych wyładowań zostały zarejestrowane jednocześnie przez cztery stacje pomiarowe systemu LSDWA (Lokalny System Detekcji Wyładowań Atmosferycznych) rozmieszczone w rejonie Warszawy, w sezonie wiosenno-letnim 2018 r. Analiza „post-time” zgromadzonych cyfrowych rekordów pomiarowych została przeprowadzona w oparciu o własne algorytmy obliczeniowe, opisane szczegółowo w artykule (Baranski i in. 2011). Jedenaście rozpatrywanych doziemnych wyładowań wielokrotnych wystąpiło w czasie dyssypacji komórki burzowej, a lokalizacje przestrzenne źródeł ich ładunku elektrycznego zostały naniesione na skorelowane czasowo mapy radarowe (PCAPPI oraz VCUT), uzyskane z radaru IMGW-PIB w Legionowie. To nałożenie wskazało, że sprzyjającym obszarem chmury burzowej, w którym dochodziło do inicjacji tych wielokrotnych wyładowań doziemnych, był rejon silnej odbiciowości radarowej (powyżej 40 dBz) rdzenia opadowego, nisko położonego w postawie chmury. Zbiorcza charakterystyka 11-stu rozpatrywanych doziemnych wyładowań wielokrotnych z burzy 25-05-2018 r. została przedstawiona w Tabeli 1.