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Physical Modeling of Positive Multistrike Lightning Formation

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Abstract: The first results of the physical modeling of positive multistrike lightning formation processes using positively charged artificial thunderstorm cells are presented. Experimental studies have shown a significant influence of the number of thunderstorm cells and groups of model hydrometeors introduced into them on the probability of the initiation of repeated strikes. It was found that with an increased number of cells and groups of model hydrometeors, the probability of the formation of repeated positive discharges increases several times. When the second group of model hydrometeors has been introduced into the artificial thunderstorm cell, or when the number of cells has been increased, the probability of the repeated discharge initiation has increased almost in three and in four times respectively. It has been revealed that, depending on the arrangement of model hydrometeor groups in artificial thundercloud cells, the formation of repeated positive discharges from them may proceed both with the "connection" of the uncharged areas of the lower cell and with the "connection" of the upper cell. The parameters of the first and repeated impulse current pulses between the positively charged cells and the ground were determined. It was found that with an increasing number of model hydrometeor groups, the value of the charge neutralized during the stages of first and repeated discharge formation increases. When forming multistrike positive discharges with the "connection" of the upper artificial thunderstorm cell, 20–30% more cloud charge has been neutralized during the repeated discharge than during the formation of a single positive discharge. It was found that the formation of positive repeated discharges was observed in about half of the cases, and that the radiation power and impulse current amplitude at repeated discharges are higher than at the first discharge. This article discusses some possible reasons for such a ratio between the parameters of the first and repeated discharges. It is assumed that the discovered significant influence of large model hydrometeor groups on the probability of the formation and the characteristics of repeated positive discharges from artificial thunderstorm cells indicate a possible key influence of hail arrays in the thundercloud on the formation of repeated strikes of positive lightning and bipolar lightning. The obtained results show that artificial thunderstorm cells of positive polarity, together with groups of large model hydrometeors, have prospects for physical modeling and the investigation of processes of the formation of positive and bipolar repeated lightning strikes.

Keywords: positive lightning; artificial positive thunderstorm cells: physical simulation; experimental investigation; first and subsequent strokes; groups of model hydrometeors; hail arrays; impulse current parameters; induced signals

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1. Introduction

One of the less-investigated problems in lightning physics is the determination of the conditions and key mechanisms of the initiation of multicomponent lightning discharges in thunderclouds [1,2]. Among them, for negative lightning, are some of the least studied and most debatable questions in the physics of thunderstorms today:

- The formation mechanisms of continuous currents and M-components;

- The mechanisms of the "connection" of neighboring regions with an increased density of negative charge (lightning cells) to the place of the first main discharge in a thundercloud;
- The mechanisms of the formation of multicomponent lightning discharges [1–3].

One of the possible influencing factors on multistrike lightning formation is considered to be the return streamers [4,5], which may play an essential role at the different stages of lightning discharge formation, and vary at positive and negative polarity [1,4–7].

Another of the least studied problems in lightning physics is the fact that positive lightning is mostly single-component. The reasons and mechanisms for positive lightning formation, which lead in most cases to the absence of repeated strikes and, at the same time, to a significant discharge of positive lightning cloud charge in one strike, are still not clear [8]. The multistrike positive discharge is estimated at the level of 1.03 to 1.5 [9–13]. At the same time, the share of multistrike flashes among the positive flashes, as estimated based on remote measurements, may vary from 4% to 37% [13–15]. The number of strikes in positive multistrike flashes varies from two to four [12–15]. A repeated strike could follow both the previous channel and a new pathway [11]. In some cases, ascending powerful positive lightning strikes were recorded at distances of several kilometers from each other with intervals from units to tens of milliseconds [16]. The observed intensification of lightning discharges by several times and more for the negative cloud-ground lightning, and especially for the positive descending lightning, is associated with the presence of large hail arrays and hail fallout.

Sometimes, it is supposed that positive lightning multiplicity may be characteristic in very powerful thunderstorm clouds and hail massifs [17,18]. In another case, it is associated with the specific arrangement of lightning cells in a thundercloud [19] (especially in winter thunderstorms [20]) or with the specific formation of bi-directional leaders [21].

Bipolar lightning discharges are also prominent among multicomponent ones [8]. They are believed to be initiated more often by ascending leaders from high objects, but may also occur in classical descending flashes. Moreover, the "typical" sequence is considered to be the first positive discharge and then the subsequent negative discharges [22,23], although the reverse sequence can also be observed [24]. It is not yet possible to explain these facts. The types of cloud structures and discharge processes involved in the formation of bipolar flares are also far from clear, although some scenarios are suggested in the literature. It is supposed that one of the mechanisms of bipolar and multicomponent lightning formation is also return streamers (leaders), which advance from the opposite sign charge area to the first discharge channel and use it further for propagation to the ground [15,25,26]. In many cases, these processes take place at heights of approximately 6 to 10 km, where the presence of hail arrays is quite probable [15].

The physical mechanism of advance (with a large horizontal component in the direction, judging from observations in thunderstorm conditions) of such a return streamer (leader) toward the first discharge is not yet clear. Moreover, in a number of cases, these return streamers (leaders) did not reach the channel of the first discharge, turned towards the ground, and formed a repeated shock at a distance of several kilometers from the place of the first strike [15,27]. The presence or absence of arrays of large cloud hydrometeors (hail arrays) may be one of the factors determining the character of the return streamer (leader)'s behavior and, hence, the possibility of forming a multicomponent and bipolar lightning. This is also evidenced by the observational data linking the lightning activity in a thundercloud with the presence of large cloud hydrometeor arrays [28–30]. The formation of streamer discharges from cloud hydrometeors of various kinds is now considered to be an important influencing factor in lightning initiation processes. It may also influence the formation of return streamers and, correspondingly, of positive and negative multicomponent lightning [31–33].

Thus, the role of hail arrays in the formation of the primary and repeated strikes of positive descending lightning from a thundercloud has not been widely studied. The introduction of a group of large model hydrometeors into the space between negatively charged artificial thunderstorm cells (ATC) showed a significant increase in the probability of the formation of repeated discharges [34]. Positive polarity ATC systems and groups of model hydrometeors were used to physically model the formation processes of repeated positive lightning strikes. This allowed us to reveal the possible electrophysical mechanisms of multicomponent positive lightning formation with the participation of hail arrays in a thundercloud and to specify their role in the full-scale discharge of the main positive charge of a thundercloud. The article presents a summary of the first results of the physical modeling (experimental studies using two vertically spaced unipolar ATCs and several groups of model hydrometeors) of the processes of positive multistrike lightning formation, and thus revealed possible key mechanisms of repeated discharge formation, including an assessment of the role of large hydrometeor arrays.

2. Experimental Measurement Complex

Physical modeling of the processes of positive multistrike lightning occurrence with the use of several positively charged ATCs has been performed on the experimental complex "GROZA" [34–36]. The basic scheme of the experimental measurement complex is shown in Figure 1.

The lower and upper ATCs (3) were located above the ground surface (a flat grounded electrostatic screen (2) at the heights of 0.9–1.3 m and 1.5–2.1 m, respectively. Two series of experimental investigations were carried out when a system of two groups of model hydrometeors (6) was introduced into the ATC. The first preliminary series was done with only the lower ATC. The second (main) series of experiments was done using two ATCs. During physical modeling of the processes during both series of experiments, the discharge current of the charged aerosol generator (1), which forms the volumetric charges of the lower and upper ATCs, was maintained at the levels of 100–125 μA and 105–130 μA, respectively. The maximum potential of a single positively charged cell reached 1.0 MV. The maximum potential of the system of two positively charged cells reached 1.5 MV. As a result, an electric field with a maximum strength of 15–20 kV/cm was created in the interval "ATC system—grounded plane" near the lower boundary of the ATC [37]. The electric field strength varied from less than 1 kV/cm to 6–8 kV/cm in different places between the cells. The time of ATC exposure in each experimental approach was 15 s.

In the experiments, the upper and lower groups of model hydrometeors were formed from four conductive cylinders 3.5 cm long. The distance between the model hydrometeors in the group was 2.9 cm. Four series of experiments were performed, in which the number of positive polarity ATCs and the number of groups of model hydrometeors introduced into them varied. The variations in the arrangement of the model hydrometeors are shown in Figure 2. In the first series of experiments, one lower ATC and one group of model hydrometeors were used (Figure 2a). The group of model hydrometeors was located near the lower boundary of the cell. The second series of experiments used one lower ATC and two groups of model hydrometeors (Figure 2b). The upper group of model hydrometeors was located inside the ATC, and the second group was located near its lower boundary. The distance between the groups was ~25–30 cm. In the third series of experiments, two ATCs and one group of model hydrometeors were used (Figure 2c). The group of model hydrometeors was located near the lower boundary of the cell. The fourth series of experiments used two ATCs and two groups of model hydrometeors (Figure 2d). The upper group of model hydrometeors was located in the space between the cells, and the lower group was located near the lower boundary of the lower cell, partially within its boundary layer. The distance between the groups was ~40–50 cm.

To register the discharge current (5), a rod electrode 0.25 m in height with the spherical top (radius 2.2 cm) (4) had been set on the grounded plane under the positively charged cells. The top was isolated from the main rod part to decrease the influence of displacement currents on the registered electric characteristics of the discharge. The currents of the first and repeated discharges between the positively charged ATCs and ground, and the electromagnetic signals induced by them on the antennas, simultaneously with their optical emission, were recorded with a Tektronix DPO7254 digital oscilloscope (Tektronix, Inc., Beaverton, OR, USA, analog bandwidth 2.5 GHz) (10) using low-inductive coaxial shunts (9) (resistance 0.5 Ohms). To register the electromagnetic radiation of the discharge phenomena, we used a system of broadband flat antennas (5–7) located: (1) on the ground surface directly near the place of formation of the first and repeated discharges (antenna A1), (2) at several meters from this place (antenna A3), and (3) at the height of the lower ATC (antenna A2).

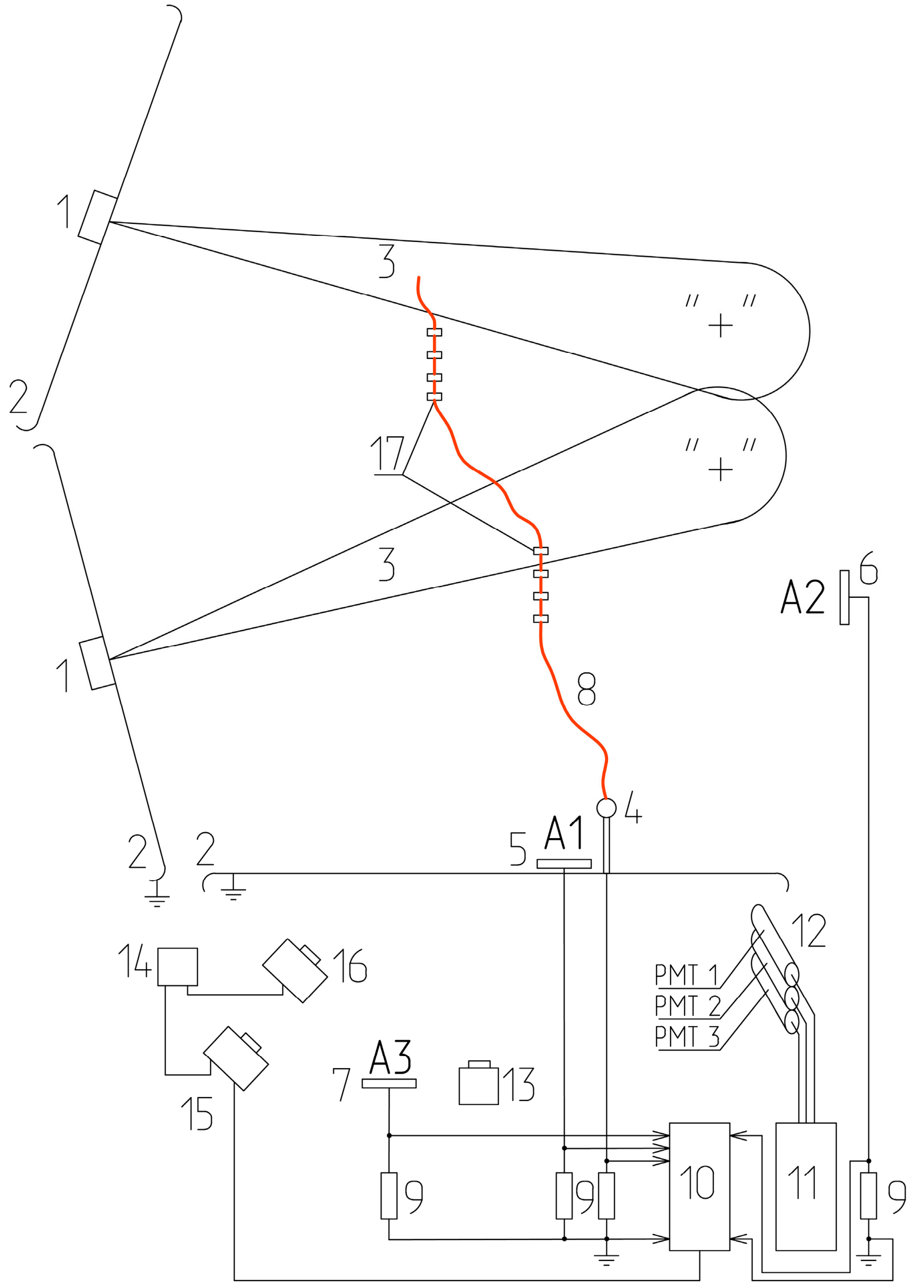


Figure 1. Basic scheme of the experimental measurement complex: 1—charged aerosol generator, 2—grounded electrostatic screens, 3—artificial thunderstorm cells of positive polarity, 4—rod electrode, 5–7—broadband flat antennas, 8—spark discharge, 9—low-inductive shunts, 10, 11—Tektronix DPO 7254 and Tektronix TDS 3054B digital storage oscilloscopes, 12—photomultiplier tube system, 13—Panasonic DMC-50 digital camera, 14—trigger generator, 15—photomultiplier tube, 16—electron-optical camera K-011, 17—model hydrometer group.

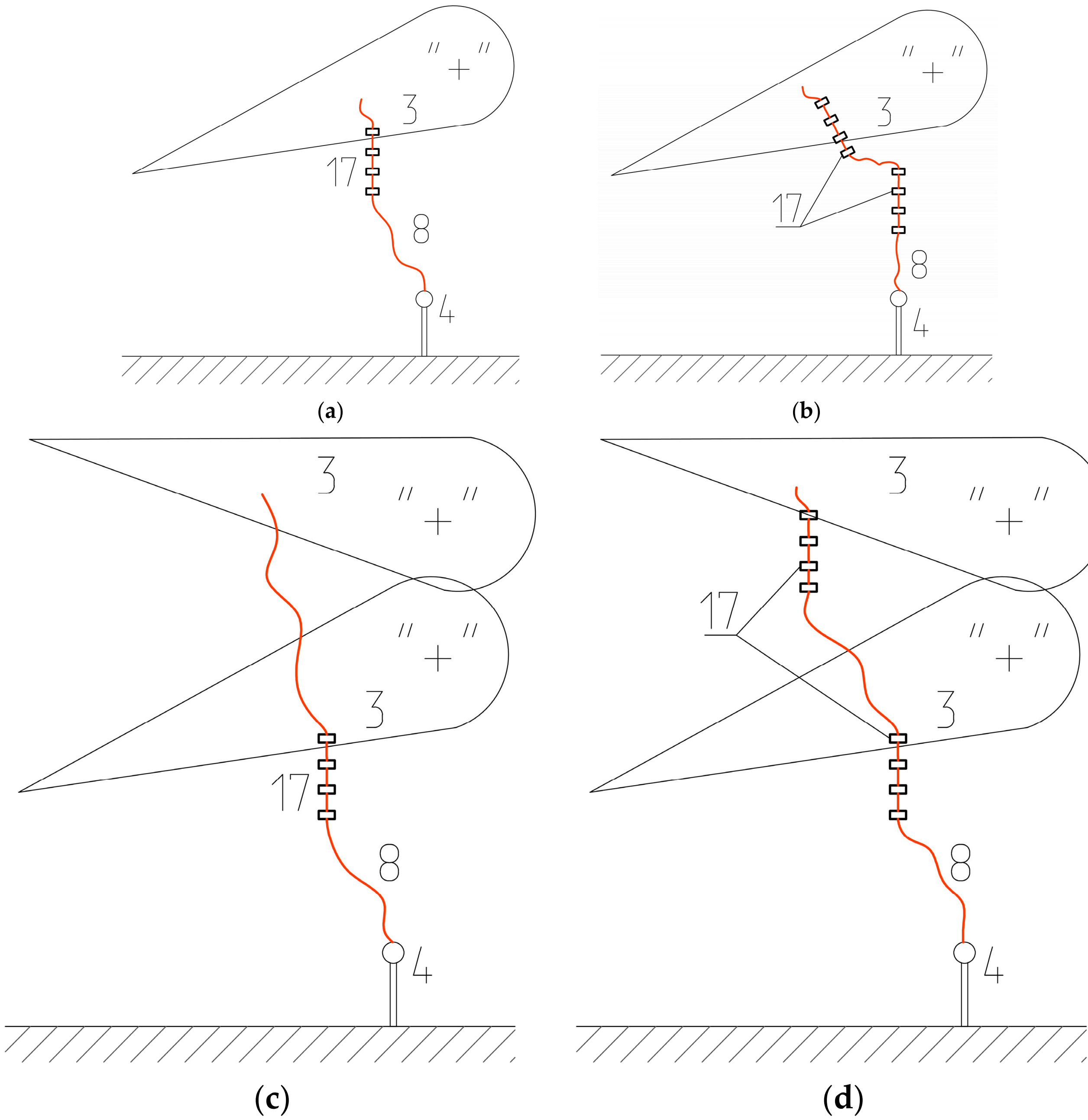


Figure 2. Variants of experimental study series with different numbers of artificial thunderstorm cells of positive polarity and model hydrometeor groups (and their arrangement): one artificial thunderstorm cell and one hydrometeor group (**a**); one artificial thunderstorm cell and two hydrometeor groups (**b**); two artificial thunderstorm cells and one hydrometeor group (**c**); two artificial thunderstorm cells and two hydrometeor groups (**d**).

Optical registration of formation of the first and repeated discharges between ATC and the ground in participation of groups of model hydrometeors and the upper ATC was performed by a digital camera 13 Panasonic DMC-50. The dynamics of formation of the first and repeated discharges were recorded by a programmable 9-frame electronic-optical camera K-011 (16), and a system of photoelectronic multipliers (12) directed (using special slits) to the different parts of the gap between the system of two vertically spaced ATCs and the rod staged on the grounded plane. The signals from the photomultiplier tube system were recorded with a Tektronix TDS3054C digital oscilloscope 11 (Tektronix, Inc., Beaverton, OR, USA, 0.5 GHz analog bandwidth).

3. Physical Modeling of Positive Multistrike Lightning Formation Processes Using Artificial Thundercloud Cells

The experiments have shown that the pattern of discharge phenomena and the probability of the formation of repeated discharges between positively charged ATCs and the ground depend on the number of cells themselves, on the number of model hydrometeor groups, and on their participation in the discharge formation.

The characteristic picture of channel discharge formation between a single (bottom) positively charged ATC and the ground, involving the bottom group of model hydrometeors (series 1), is shown in Figure 3.

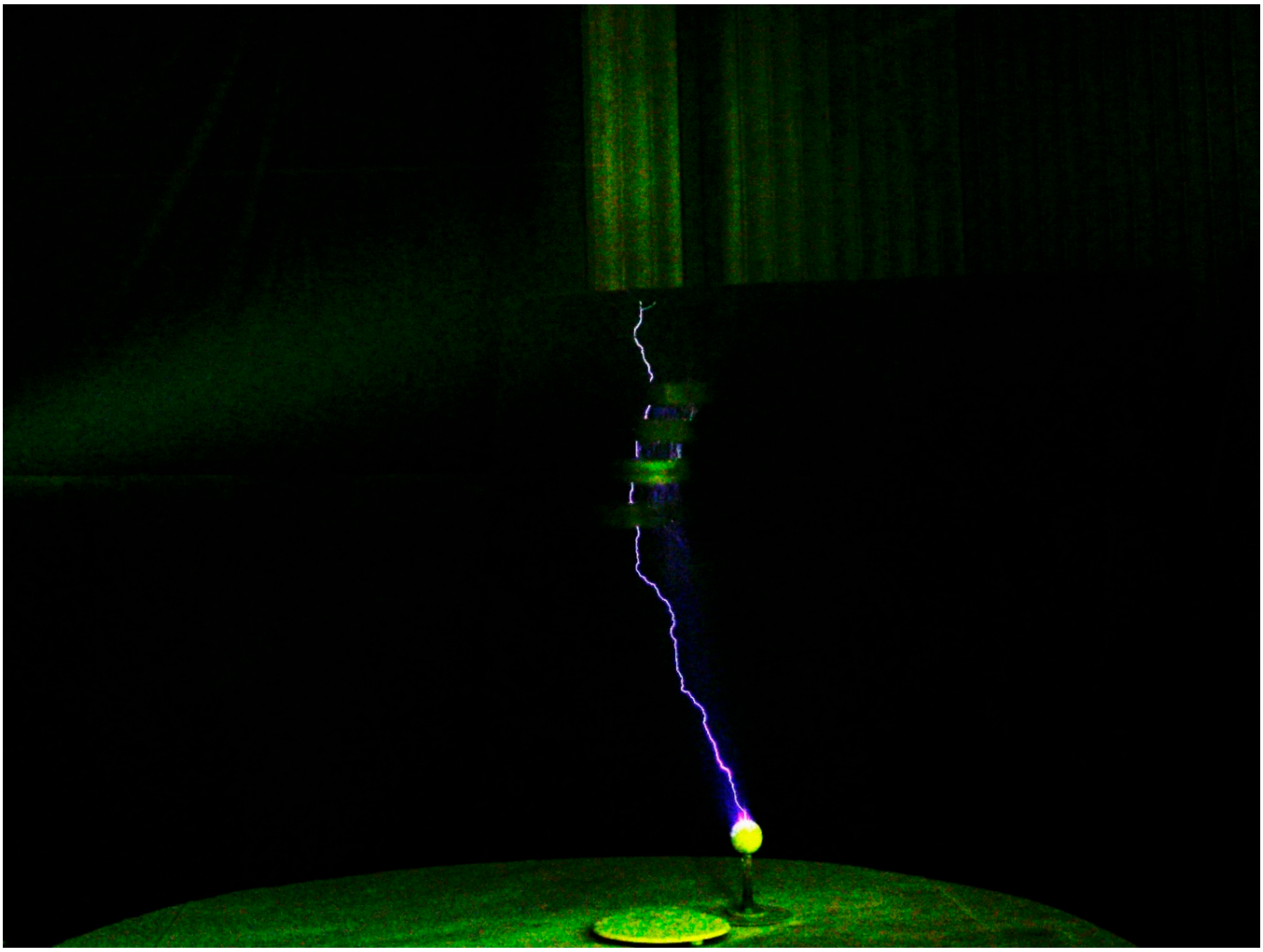


Figure 3. Discharge formation between a single positively charged thunderstorm cell and the ground involving one group of model hydrometeors.

In this case, there is a partial penetration of the discharge channels inside the positively charged ATC due to their formation from the upper model hydrometeor. In this case, a relatively small volume of the ATC is involved, the probability of formation of repeated discharges is relatively small (less than 7% of the total experiments), and the main stage current in most cases has a pronounced single-pulse character (Figure 4). The current amplitude of such a single pulse was in the range from 10 A to 194 A.

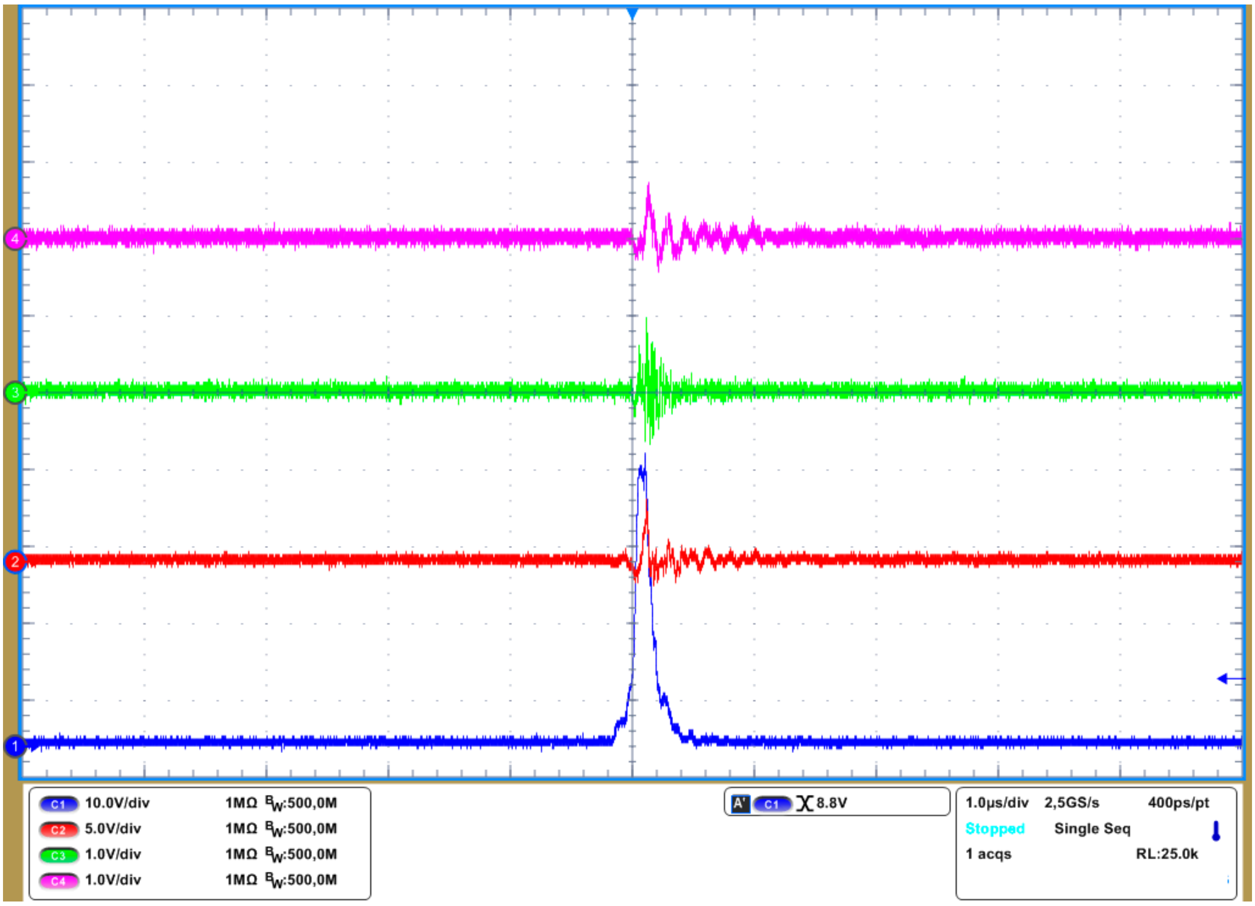


Figure 4. Characteristic oscillogram of the main stage discharge current pulse (blue signal) between a single artificial positively charged thundercloud cell and the ground involving one group of model hydrometeors and signals, registered by antennas A1–A3 (red, green and magenta signals resp.).

The parameters of the first and repeated (if any) current pulses for the main stage of discharge from the positive polarity ATC with the participation of one group of model hydrometeors (series 1) are summarized in Table 1: |Imax|—pulse amplitude; |Qsum|—transferred (neutralized) charge; $a_{0.1}$—current pulse steepness at 0.1–0.9 of maximum; $a_{0.3}$—current pulse steepness at 0.3–0.9 of maximum.

Table 1. Parameters of main stage discharge current pulses from a single artificial thunderstorm cell of positive polarity involving one group of model hydrometeors (mean value, range).

	Discharge Proportion, %	|Imax|, A	|Qsum|, µQ	$a_{0.1}$, A/ns	$a_{0.3}$, A/ns
First discharge	7	22.7 [20.8 ÷ 25.6]	2.89 [2.53 ÷ 3.4]	0.33 [0.27 ÷ 0.39]	0.53 [0.47 ÷ 0.61]
Repeated discharges		53.6 [35.2 ÷ 78.4]	8.77 [5.39 ÷ 11.12]	0.94 [0.59 ÷ 1.58]	1.08 [0.56 ÷ 1.9]
Singular discharges	93	101.2 [10.4 ÷ 193.6]	13.97 [1.17 ÷ 24.51]	1.59 [0.04 ÷ 14.0]	2.14 [0.07 ÷ 13.0]

The characteristic picture of channel discharge formation between a single (bottom) positively charged ATC and the ground, with the participation of two groups of model hydrometeors (series 2), is shown in Figure 5. In this case, we observe deeper penetration of the discharge channels inside the ATC due to the participation of the group of model hydrometeors inside the cell in their formation. At the same time, as compared to the first series, the probability of the formation of repeated discharges has significantly increased (up to 19% of the total experimental approaches). The characteristic oscillogram of current pulses of the first and repeated discharges from the positive polarity ATC is shown in Figure 6. The time interval between the first and second current pulses usually did not exceed 1.0–1.2 μs. In other cases, as in the first series (Figure 4), the main stage current had a pronounced single-pulse character, although both groups of model hydrometeors can take part in the formation of the discharge (Figure 7). At the same time, the amplitude of the single pulse of the main stage current changed, on average, by 30%.

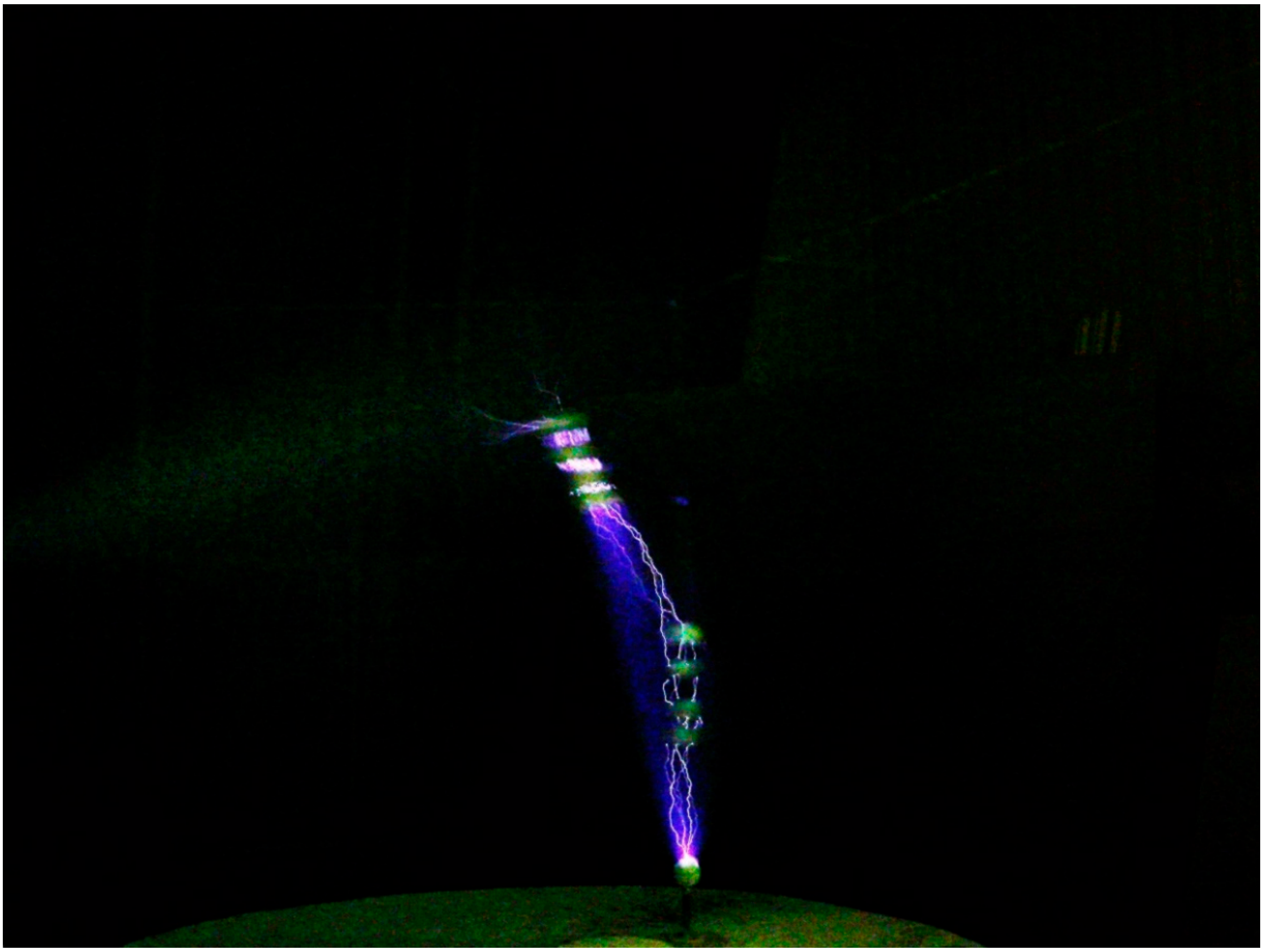


Figure 5. Discharge formation between a single artificial positively charged thunderstorm cell and the ground involving two groups of model hydrometeors.

The parameters of the first and repeated (if any) current pulses for the main stage of the discharge from the positive polarity ATC with participation of two groups of model hydrometeors (series 2) are summarized in Table 2.

The characteristic picture of channel discharge formation between the system of two positively charged ATCs (lower and upper) and the ground, with the participation of the lower group of model hydrometeors (series 3), in general, corresponds to the picture of discharge formation for a single cell with one group of model hydrometeors (Figure 3). The differences are as follows:

- Due to the influence of the electric field of the upper ATC, there is a deeper penetration of the discharge system developing from the upper model hydrometeors in the group inside the lower ATC.

- The probability of the formation of repeated discharges has increased (up to 27% of all experimental approaches).

Table 2. Parameters of main stage discharge current pulses from a single artificial thunderstorm cell of positive polarity, involving two groups of model hydrometeors (mean value, range).

	Discharge Proportion, %	∣Imax∣, A	∣Qsum∣, μQ	$a_{0.1}$, A/ns	$a_{0.3}$, A/ns
First discharge	19	26.7 [12.9 ÷ 44.8]	2.81 [1.11 ÷ 5.13]	0.55 [0.09 ÷ 1.0]	0.94 [0.11 ÷ 2.07]
Repeated discharges		34.0 [12.0 ÷ 59.0]	7.11 [1.99 ÷ 11.72]	0.53 [0.04 ÷ 1.94]	0.89 [0.13 ÷ 2.36]
Singular discharges	81	72.2 [12.3 ÷ 164.2]	11.66 [0.64 ÷ 23.06]	0.97 [0.13 ÷ 5.15]	1.71 [0.13 ÷ 6.34]

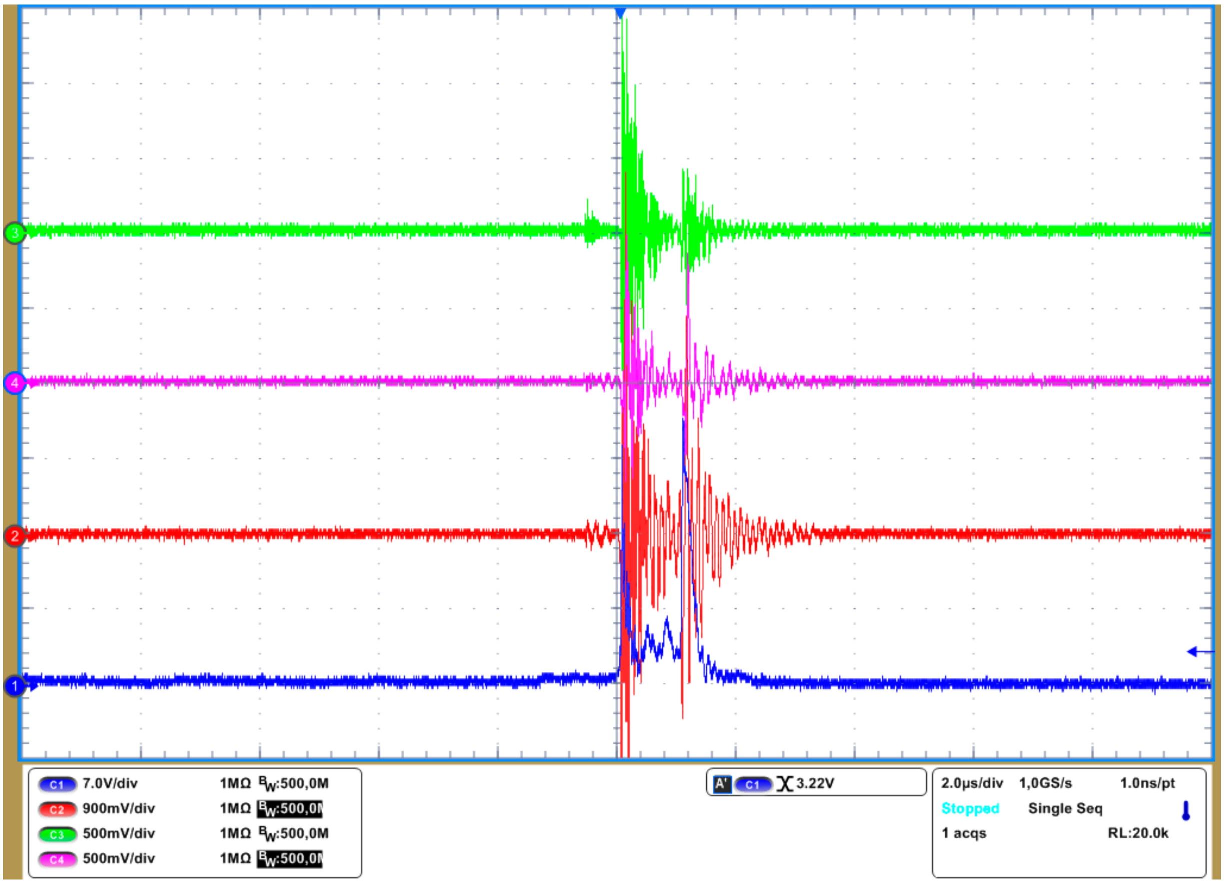


Figure 6. Characteristic oscillogram of the first and repeated discharge current pulses (blue signal) between a single artificial positively charged thundercloud cell and the ground involving two groups of model hydrometeors and signals, registered by antennas A1–A3 (red, green and magenta signals resp.).

For the cases of the formation of single-pulse discharges, the average current amplitude remains approximately at the same level as in the first series of experimental studies, varying in the range from 27 A to 186 A.

The parameters of the first and repeated (if any) current pulses for the main stage of the discharge from the positive polarity ATC system involving one group of model hydrometeors (series 3) are summarized in Table 3.

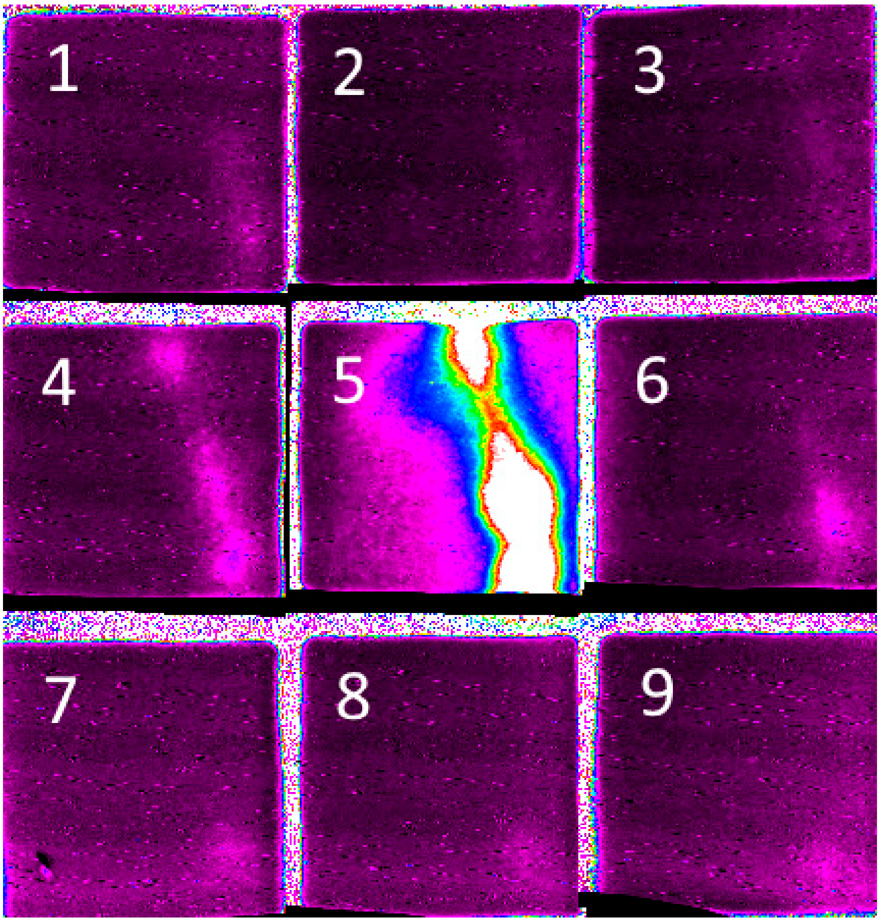


Figure 7. Characteristic dynamics of single discharge formation from an artificial thunderstorm cell of positive polarity with the participation of lower and upper groups of model hydrometeors (frame size 75 × 75 cm, frame duration 1.5 µs, pause between frames 0.1 µs).

Table 3. Parameters of main stage discharge current pulses from the system of artificial thundercloud cells of positive polarity involving one group of model hydrometeors (mean value, range).

	Discharge Proportion, %	|Imax|, A	|Qsum|, µQ	$a_{0.1}$, A/ns	$a_{0.3}$, A/ns
First discharge	27	25.5 [12.8 ÷ 61.6]	2.64 [1.69 ÷ 3.63]	1.05 [0.1 ÷ 4.78]	5.24 [0.21 ÷ 30.8]
Repeated discharges		57.9 [28.8 ÷ 110.4]	12.68 [5.45 ÷ 18.63]	0.84 [0.11 ÷ 1.44]	1.27 [0.1 ÷ 2.61]
Singular discharges	73	86.1 [27.2 ÷ 182.4]	13.33 [2.44 ÷ 24.80]	1.76 [0.05 ÷ 13.2]	3.61 [0.05 ÷ 32.0]

The characteristic patterns of channel discharge formation between the system of two positively charged ATCs and the ground at the introduction of the lower and upper groups of model hydrometeors (series 4) are shown in Figure 8 and in Figure 9. In the first case, only the lower group of model hydrometeors participates in channel discharge formation (Figure 8). Here, a deeper penetration of the discharge channels inside the lower ATC is observed, the probability of the formation of repeated discharges is very small, and the main stage current has a pronounced single-pulse character (Figure 10). In both series of experiments, the current pulse amplitude of such a single pulse varied in the range from 35 A to about 200 A.

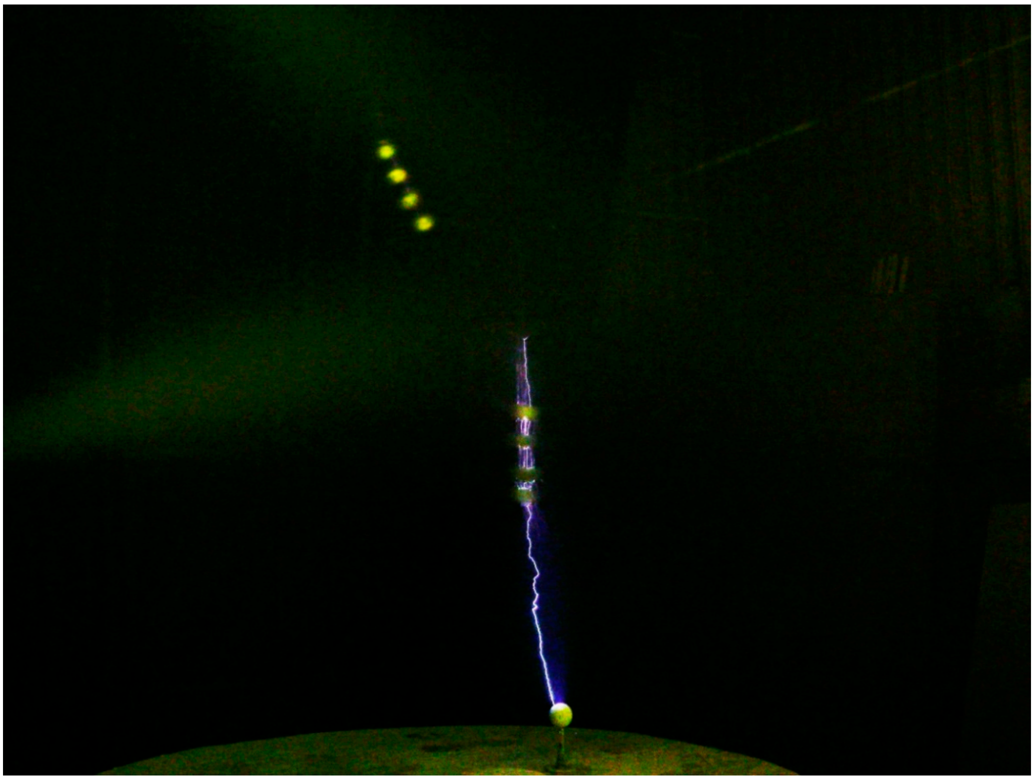


Figure 8. Discharge formation between the system of artificial positively charged thunderstorm cells and the ground involving only the lower group of model hydrometeors.

Figure 9. Discharge formation between the system of artificial positively charged thunderstorm cells and the ground involving the lower and upper groups of model hydrometeors.

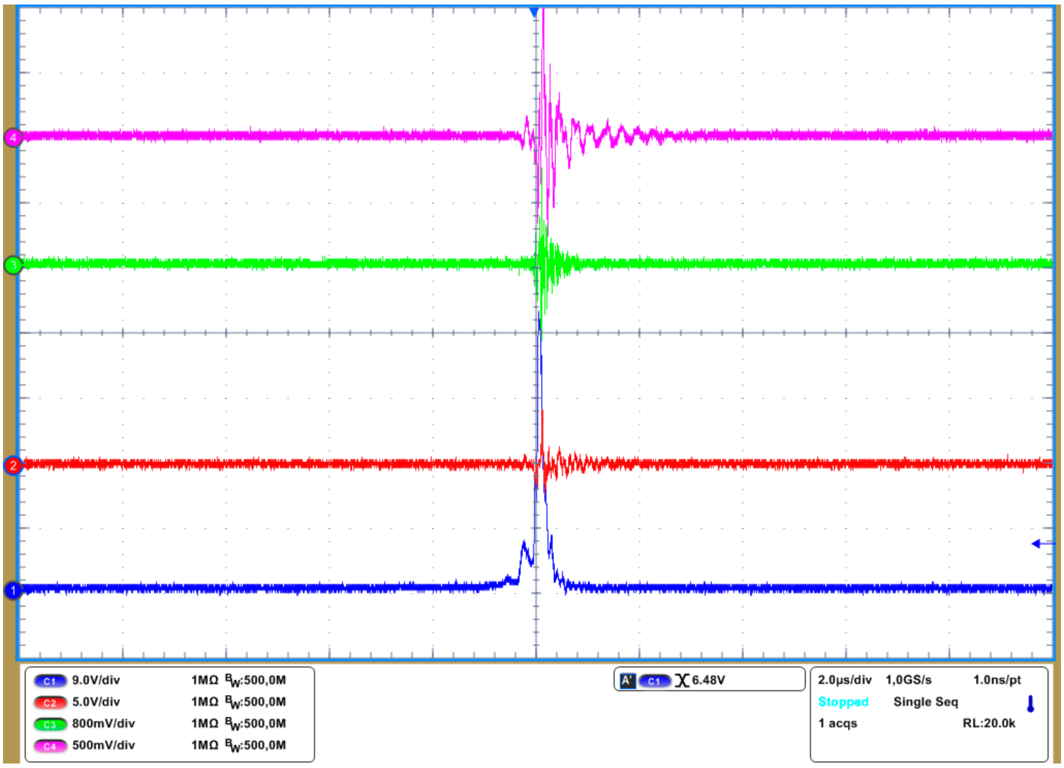


Figure 10. Characteristic oscillogram of the current pulse (blue signal) of the main discharge stage with participation of only the lower group of model hydrometeors and signals, registered by antennas A1–A3 (red, green and magenta signals resp.).

In the second case, the development of channel discharges between the system of positively charged ATCs and the ground occurs with the "connection" of the upper ATC and the formation of repeated discharges (Figure 9). The probability of the formation of repeated discharges is 20% of all experimental approaches. The oscillogram of the current corresponding to the characteristic case of the formation of the first discharge from the lower ATC and repeated discharges with the connection of the upper ATC is shown in Figure 11.

The characteristic dynamics of the formation of the first and repeated discharges from the positive polarity ATC system, with the participation of the lower and upper groups of model hydrometeors, are shown in Figure 12, where the repeated discharge is significantly more powerful than the first discharge, and in Figure 13, where the repeated discharge is weaker than the first discharge.

The parameters of the first and repeated (if any) current pulses for the main stage of the discharge from the positive polarity ATC system involving two groups of model hydrometeors (series 4) are summarized in Table 4.

Table 4. Parameters of main stage discharge current pulses from the system of artificial thunderstorm cells of positive polarity involving two groups of model hydrometeors (mean value, range).

	Discharge Proportion, %	**∣Imax∣, A**	**∣Qsum∣, µQ**	$a_{0.1}$**, A/ns**	$a_{0.3}$**, A/ns**
First discharge	20	42.6 [15.2 ÷ 89.6]	7.5 [2.17 ÷ 17.03]	0.55 [0.11 ÷ 2.77]	0.8 [0.12 ÷ 3.49]
Repeated discharges		68.6 [10.1 ÷ 145.6]	13.49 [2.19 ÷ 27.39]	0.58 [0.03 ÷ 1.47]	0.86 [0.05 ÷ 2.2]
Singular discharges	80	109 [30.4 ÷ 196]	17.62 [2.36 ÷ 29.83]	1.34 [0.16 ÷ 10]	2.54 [0.2 ÷ 43.73]

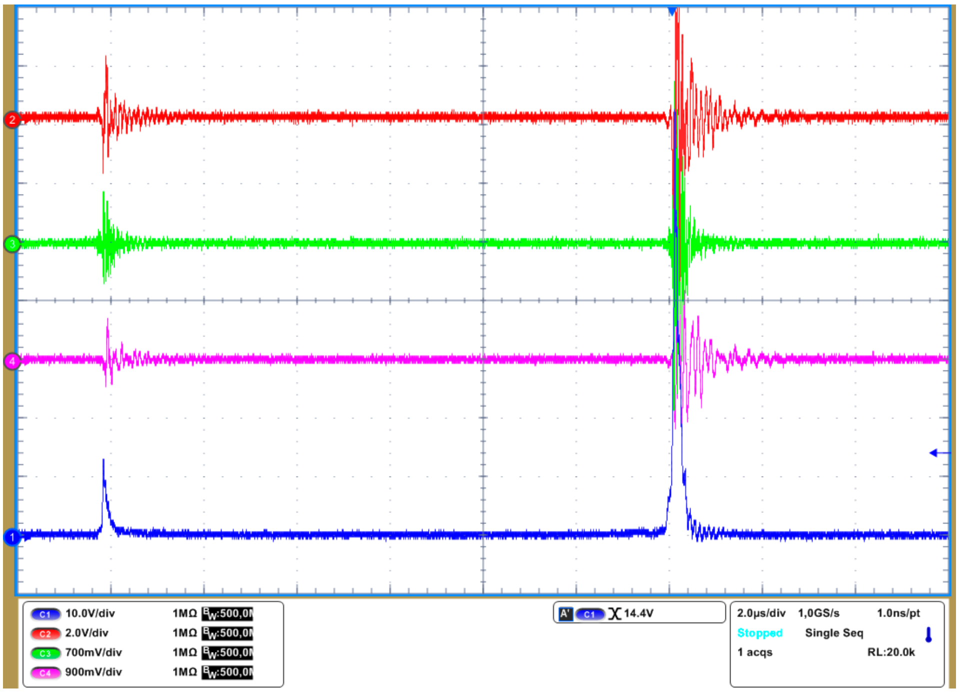


Figure 11. Characteristic oscillogram of the first and repeated discharge current pulse (blue signal) from the system of artificial thunderstorm cells of positive polarity with the participation of lower and upper groups of model hydrometeors and signals, registered by antennas A1–A3 (red, green and magenta signals resp.).

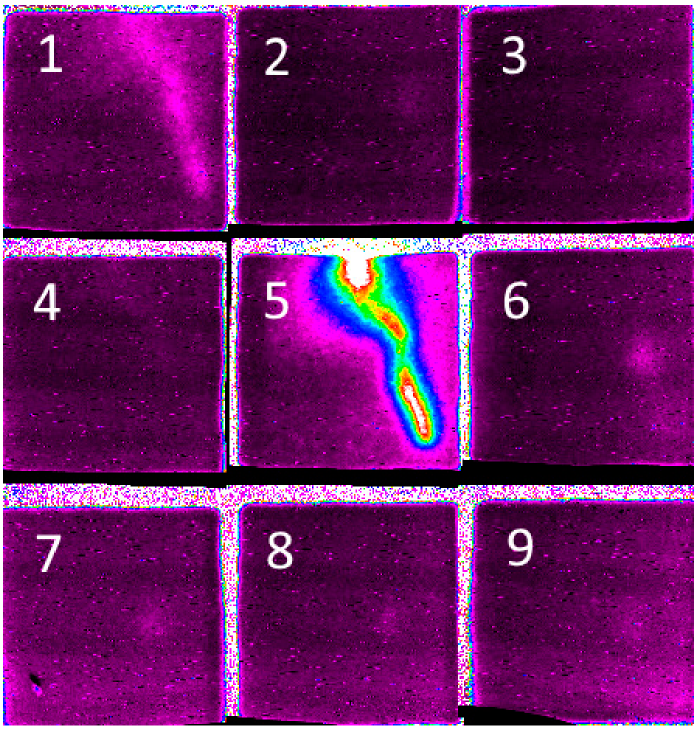


Figure 12. Characteristic dynamics of the formation of the first and repeated discharges from the system of artificial thunderstorm cells of positive polarity with participation of lower and upper groups of model hydrometeors at a more powerful repeated discharge (frame size 85 × 85 cm, frame duration 2.5 µs, pause between frames 0.1 µs).

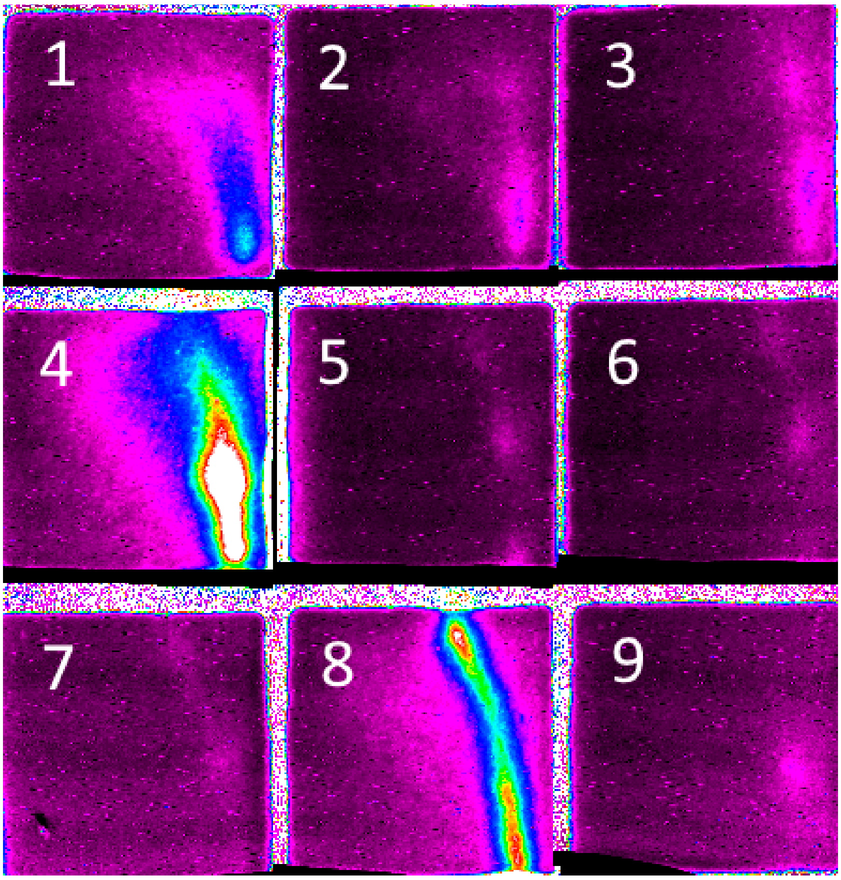


Figure 13. Characteristic dynamics of formation of the first and repeated discharge from the system of artificial thunderstorm cells of positive polarity with the participation of lower and upper groups of model hydrometeors at a more powerful first discharge (frame size 85 × 85 cm, frame duration 2.5 μs, pause 0.1 μs).

When two positive-polarity ATCs are used and two groups of model hydrometeors are introduced into them, the duration of the pause between the first discharge and the repeated discharge, as compared to the physical simulation cases using single cells and single groups of hydrometeors, increases, being on average 2.5–3.5 μs. Sometimes the pause exceeds 10 μs when the upper ATC takes an active part in the formation of the repeated discharge.

4. Analysis of Results and Discussion

Physical modeling of the formation of positive multistrike lightning using positive polarity ATCs showed that the formation of repeated discharges from positive polarity ATCs significantly depends on the number of positively charged cells and the number of groups of model hydrometeors injected into them. Adding the upper ATC almost fourfold increased the probability of the initiation of positive repeated discharges from the lower ATC by a single group of model hydrometeors (Tables 1 and 3). Introducing the second group of model hydrometeors into the single positive-polarity ATC increased the probability of forming repeated discharges from it 2.8-fold (Tables 1 and 2). At the same time, the introduction of the second group of model hydrometeors into the gap between the lower and upper ATCs of positive polarity did not lead to an increase in the probability of repeated discharge formation from them (Tables 3 and 4). This suggests that an important factor in the initiation and subsequent formation of repeated discharges from positive-polarity ATC systems is the location of the model hydrometeor groups in them. For the two-cell structure, the introduction of two groups of model hydrometeors increased the cloud charge by 30%, which was neutralized during the first and repeated discharges from the positively charged cell system.

The analysis of the experimental results showed that when physically simulating the processes of the formation of positive multistrike lightning with the use of positive polarity ATC at all variants of the experimental series, the amplitude of the repeated-discharge current pulse in 40–50% of cases was higher than the amplitude of the first-discharge current pulse (Figure 14b). The same tendency was demonstrated by the amplitude values of Imax.a signals induced on antenna A3 by the first and repeated discharges (Figure 15), especially in the presence of the second group of model hydrometeors in the space between the ATCs of positive polarity (Figure 15b).

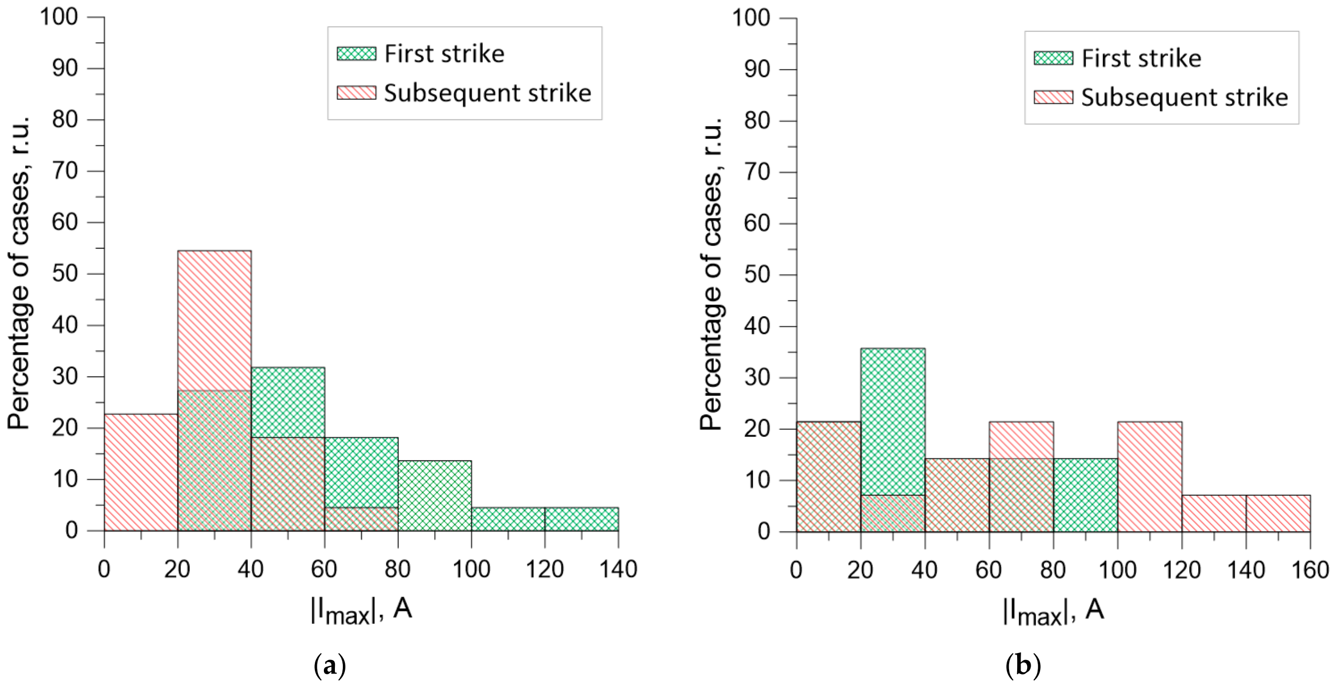
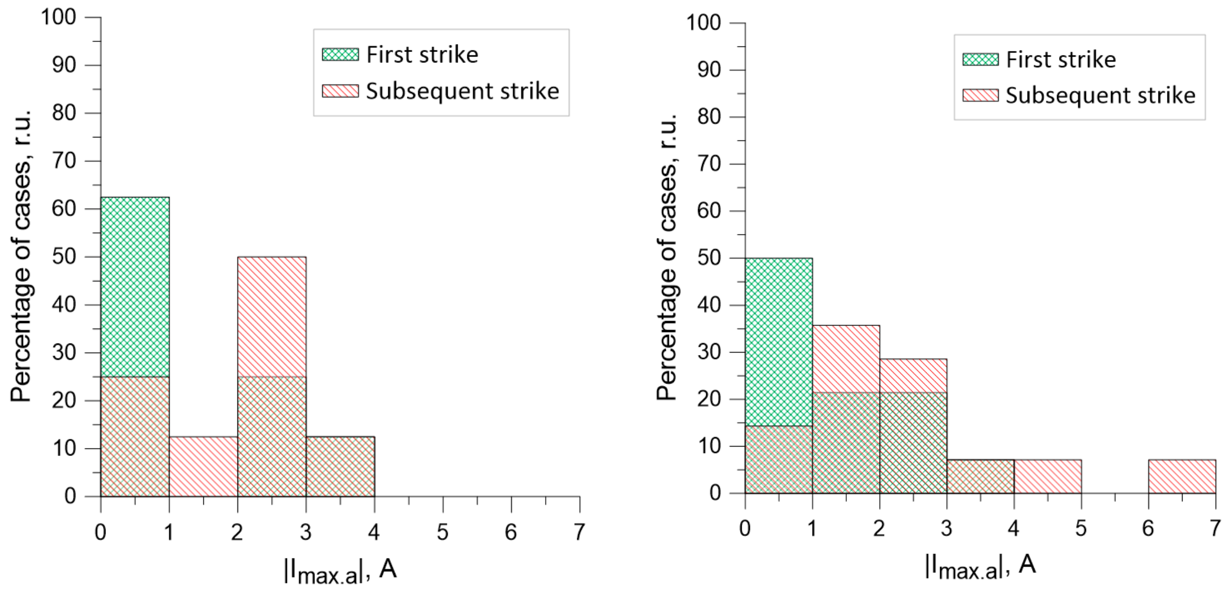


Figure 14. Distribution of current pulse amplitude values of the first and repeated discharges at negative polarity of artificial thunderstorm cells (**a**) and at positive polarity of artificial thunderstorm cells (**b**).

Such results of physical modeling correlate with the cases of multistrike positive lightning observed during winter thunderstorms in Japan (Table 1 in [20]), when the values of current pulse amplitudes of repeated (second or third) strikes were comparable to or significantly higher than the values of the current pulse amplitudes of the first strike (this is often characteristic for the cases where positive lightning has more than two strikes [12]). At the same time, such correlations differ from the estimations of the current amplitudes of multi-stroke positive lightning on the basis of lightning direction finding systems [9] (where, on average, the values of the amplitudes of the repeated strike currents are estimated to be 20–30% smaller than those of the first strike) and [10] (where such a trend of higher values of the current of repeated strikes was observed only in 17% of cases). It may be related to the fact that in this experiment, a group of lower model hydrometeors participated in the physical modeling of the formation processes of positive multistrike lightning using the ATC in the initiation of the positive leader leading to the first main discharge. Although, as noted in [10], the mechanism of the formation of positive leaders initiating the first strikes may be more diverse and complex. Several variants (scenarios) are possible based on the bipolar leader concept [38], depending on the slow, fast or slow-fast bi-directional development and behavior of the negative leader inside the thunderstorm cloud. These variants (scenarios), as suggested by [11], also depend on the number and location of the positive charge regions in the thunderstorm cloud.



(a) (b)

Figure 15. Distribution of signal amplitude values of Imax.a, induced at the antenna A3 by the first and repeated discharges: (**a**)—variant in Figure 2c; (**b**)—variant in Figure 2d.

It should also be noted that such results differ from what was determined when physically simulating the first and repeated discharges from the negatively charged ATC system [39] (Figure 14a), and from observational data on negative natural lightning [40], where the amplitude of the current pulse of repeated strikes was on average much lower than the amplitude of the first strike current. It can also be assumed that the ratio of the amplitudes of the first and repeated current pulses in multistrike positive lightning depends on the region and season, where and when such lightning was formed, and the specific conditions of the size, number and location of positive charge areas in the thundercloud and hail massifs in it that can take shape [13,14].

It is possible that, specifically, the presence of large hydrometeor (hail massif) groups near the boundary region between the main negative and positive charges of a thundercloud may contribute to "switching" the discharge processes from one charge center to the opposite one due to the way these meteors stimulate the processes of the initiation and propagation of a reversible polarity leader [41] or a negative leader [42] and, subsequently, to the formation of bipolar lightning (e.g., according to the mechanism suggested in [15,41,42]). In principle, the same hail arrays in a thundercloud may stimulate the propagation of the negative leader into the region of the main positive charge and lead to the initiation of repeated discharges of positive lightning or bipolar lightning, including those with a new attachment point on the ground surface [43].

Of course, the use of ATCs and groups of model hydrometeors cannot reflect all the nuances of the discharge processes in a natural thunderstorm cloud, but they allow us to approach them. They allow us to physically simulate and study the fine details of discharge formation inside thunderstorm cells, which cannot be discerned remotely during a thunderstorm or a simulation using pulse voltage generators and metal electrode systems. One of the possible prospects for the use of ATCs of positive polarity is the physical simulation of repeated strikes, the trajectory of which does not coincide with the initial one.

5. Conclusions

The first results of the physical modeling of the formation of positive repeated lightning discharges using the positive polarity ATC demonstrated a significant influence of the number of lightning cells and the number of groups of model hydrometeors injected into them on the probability of initiating repeated strikes. As the number of positively charged thunderstorm cells and groups of model hydrometeors increases, the probability of forming repeated positive discharges increases several times:

- When the second group of model hydrometeors was introduced into a single cell, the probability of initiating repeated discharges increased by almost three times.
- The presence of the second artificial thundercloud cell increased the probability of the initiation of repeated discharges by a single group of model hydrometeors by almost four times.

It was found that, depending on the arrangement of model hydrometeor groups in the ATCs, the formation of repeated positive discharges may proceed both with the "connection" of the areas of the lower cell uncharged during the first discharge, and with the "connection" of the upper ATC. It was established that as the number of model hydrometeor groups increases, the amount of charge neutralized during the first and repeated discharges increases as well. In the case of the formation of multistrike positive discharges from a system of ATCs with "connection" of the upper cell, 20–30% more cloud charge is neutralized at the repeated discharge than at the formation of a single positive discharge. This indicates that large hydrometeors (hailstones), firstly, promote the formation of more powerful streamer discharges, and secondly, can promote the advance of discharge processes deep into the positively charged regions, providing additional neutralization of the cloud charge.

In half of the cases, the radiation power and current pulse amplitude during repeated discharges from positively charged cells was higher than during the first discharge. This is possibly connected both with the location of the input places of the model hydrometeor groups in the ATC and with the charge magnitude and location of the cells themselves in relation to each other and to the ground.

Such a significant influence of groups of large model hydrometeors on the probability of the formation and characteristics of repeated positive discharges from the ATC indicates a possible key influence of hail arrays in a thundercloud on the formation of repeated strikes of positive lightning and bipolar lightning. Observations of natural lightning show that there is a correlation between the intensity of lightning jumps and the presence of hail in a thundercloud [30,44,45]. It would be interesting to carry out observations under natural thunderstorm conditions and check for a correlation between the presence and dynamics of hail arrays in a cloud and the probability of the initiation of repeated positive lightning discharges. The use of positive-polarity ATCs and groups of model hydrometeors opens up new possibilities for physical modeling and the investigation of the formation of positive repeated lightning strikes, including their formation from different parts of the thunderstorm cloud and with different locations of the first and repeated strikes on the ground surface.

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