Peculiarities of Electromagnetic Radiation Spectrum of Discharges Initiated by Hydrometeors between Artificial Thunderstorm Cell and Ground


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Abstract—Results of experimental investigation of the influence of the hydrometeor array disposed inside the artificial thunderstorm cell and near its boundary on the spectral characteristics of spark discharge between the cloud and the ground and its electromagnetic radiation have presented. Peculiarities of the Fourier and wavelet (wavelet “Mexican hat”) electromagnetic spectrum of discharges forming on the hydrometeor array in the negatively and positively charged aerosol clouds have analyzed. Application of the received results to the electromagnetic radiation from discharge phenomena in natural thunderclouds has discussed.

Keywords—artificial thunderstorm cell; hydrometeor array; discharge; experimental investigation; negatively and positively charged cloud; spectral characteristics; Fourier and wavelet analysis

I. INTRODUCTION

Lightning radiation has a large spectrum from very low frequencies up to very high frequencies characterizing different discharge phenomena in thunderclouds [1, 2]. Observation and analysis of the lightning electromagnetic fields is important as for to understand the physics of the lightning discharge, as to improve the effectiveness of the lightning detection systems. For the lightning detection systems, two problems should be solved [3]. First, to find possible approaches to separate correctly the cloud and ground parts of the lightning discharge. Second, to determine possible correlation dependences between the parameters of return stroke and discharge processes near the ground and in the cloud before and after it and the parameters and spectral characteristics of the electromagnetic radiation registered by the antennas during a lightning discharge formation. Triggered lightning is one of the means to investigate the mentioned problems [4]. Especially it is important to relate correctly the corresponding discharge processes in thunderclouds to the lightning electromagnetic fields registered by the very high frequency lightning detection systems at near range [5-8]. Cloud discharges developing in the different parts of thundercloud obviously pass through the regions containing a large quantity of hydrometeors of various types. It is important to understand how the arrays of hydrometeors could influence on the peculiarities of discharge development in the negatively or positively charged thunderstorm cells and on the peculiarities of the corresponding electromagnetic radiation registered on the ground in near region. Application of the wavelet analysis for the lightning electromagnetic fields is the modern trend for the detail analysis of the peculiarities of the electromagnetic radiation of the discharge phenomena in thunderclouds [9-13]. Investigations of the discharges initiated by model hydrometeors between the artificial thundercloud cell of negative or positive polarity and the ground and its electromagnetic radiation simultaneously with wavelet analysis could help to advance the solving of the mentioned problems.

II. METHODS AND RESULTS

A. Experimental setup and data processing

Investigations of the influence of the model hydrometeors on the electromagnetic radiation of the discharges from an artificial thunderstorm cell of negative or positive polarity have carried out on the experimental complex described in [14]. In experiments, the system of the plate antennas situated on the different distance and height from the place of discharges initiated by the model hydrometeor array has used for the registering of the electromagnetic radiation (Fig. 1). First plate Antenna A1 has situated on the ground immediately near to the grounded rod electrode. Second plate Antenna A2 has situated on the wall of an aerosol chamber at the distance of two meters from the grounded rod electrode. Height of the second plate antenna location has corresponded to the region height of the bottom boundary of an artificial thunderstorm cell where the hydrometeor array situated. Third plate Antenna A3 has situated on the ground at the distance of three meters from the grounded rod electrode. These disc antennas with the rounded edges (to prevent a corona discharge appearance) that were grounded through the low inductive shunts registered the velocity of change of the electric field strength dE/dt in the places of their disposition due to the occurring discharges.

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Figure 1. Characteristic picture of discharge formation on the model hydrometeor array disposed near the boundary of the artificial thunderstorm cell and the disposition of antennas

Therefore, plate antennas A1, A2, and A3 have the bandwidth limitation first of all due to the digital oscilloscope characteristics (2.5 GHz for DPO 7254). Digital Storage Oscilloscope Tektronix DPO 7254 has used for the data recording with 0.4 ns time resolution.

For determination of the spectral characteristics of the discharge current and the displacement current registered by the antennas, the Fourier and wavelet analysis has used. In difference to the Fourier analysis, the wavelet analysis could show the changing of the frequency spectrum of the registered signals across the considered time interval. As a result, we can compare the frequency spectra of the different registered signals (for example, the discharge current impulse, optical picture of the discharge development in time fixed with the CCD camera or the system of photomultipliers, and the impulse of its electromagnetic radiation registered by the antennas) for the same time intervals. That allows the connecting of the characteristic frequencies of all registered signals with the peculiarities of the concrete stage of the discharge development and its parameters.

Nowadays, the different kinds of wavelets have used for the atmospherics and lightning electromagnetic radiation analysis: DOG wavelets [9-11, 15, 16], Laplace wavelet [12], Morle wavelet [17]. The DOG wavelet “Mexican hat” has chosen for analysis because it is more appropriate to consider the fast transient signals, such as the return stroke and the cloud discharges.

For every interesting time interval, the characteristics frequency spectrum ranges have been established. Two kinds of the characteristic frequencies of the wavelet spectrum were in a consideration: the maximal frequency $f_{\text{MAX}}$ of the frequency range, and frequency $f(C_{\text{MAX}})$ corresponding the maximal intensity $C_{\text{MAX}}$ in the wavelet spectrum. Special program for the processing of the wavelet spectrum and the determination of such characteristic frequencies has developed. It allows automatically finding in the wavelet spectrum of the $C_{\text{MAX}}$ and the corresponding $f(C_{\text{MAX}})$.

B. Influence of hydrometeor array on the electromagnetic radiation of discharge between negative artificial thunderstorm cell and ground

As it has been noted in [14] in the negatively charged artificial thunderstorm cell the hydrometeor array could initiate the cloud discharges on the hydrometeor array (variant GMN1), the channel discharges between the cloud and the ground using the hydrometeor array (variant GMN2), and the channel discharges between the cloud and the ground past the hydrometeor array (variant GMN3).

Typical signals registered by the antennas during cloud discharges on the hydrometeor array have shown in Fig. 2. Discharge processes on the hydrometeor array disposed near the negatively charged artificial thunderstorm cell boundaries have an impulse character. That leads to the appearance of the impulse pockets on the signals registered by the plate antennas A1 and A2. Spectral characteristics of signals registered by the antennas show the clearly observed super high frequencies up to some gigahertzes (Fig. 3). Apparently, discharge processes developing between neighboring hydrometeors in array are the source of such high frequencies.

Variant GMN2 (formation of the channel discharges between the artificial thunderstorm cell and the ground with participation of the hydrometeor array) is characterized with the strong impulse current of the final stage and powerful electromagnetic radiation (Fig. 4). Moreover, discharge processes on the hydrometeor array pass during some microseconds after the final stage ending and influence on the content of the electromagnetic radiation registered by the antennas.

Figure 2. Oscillograms of the signal registered by the plate antennas A1 (curve 2, shunt 0.5 Ohm), A2 (curve 3, shunt 0.5 Ohm), A3 (curve 4, shunt 0.5 Ohm) for cloud discharges on the hydrometeor array in the artificial thunderstorm cell of negative polarity
Figure 3. Characteristic Fourier spectrum of signal registered by the plane antenna A2 for cloud discharge formation on the model hydrometeor array disposed near the boundary of the artificial thunderstorm cell of the negative polarity.

Fourier and wavelet spectra of the signals registered by the broadband plate antennas shows the frequency corresponding the maximal intensity in spectrum in the ranges 1-60 MHz for signals registered by the antenna A1, 30-300 MHz for signals registered by the antenna A2, and 3-65 MHz for signals registered by the antenna A3 (Fig. 5). In average, these frequency ranges shift less into more high values in comparison with case of the cloud discharges that form on the model hydrometeor array.

When spark discharge passes besides the hydrometeor array the spectral characteristics of the electromagnetic radiation of the channel discharges between the charged aerosol cloud and the ground show a similar behavior.

Figure 4. Oscillograms of the discharge current between the cloud and the ground (curve 1, shunt 0.5 Ohm), of the signal registered by the plate antennas A1 (curve 2, shunt 0.5 Ohm), A2 (curve 3, shunt 0.5 Ohm), A3 (curve 4, shunt 0.5 Ohm) for channel discharges on the hydrometeor array in the artificial thunderstorm cell of negative polarity.

Figure 5. Wavelet spectrum of the signal registered by the plate antenna A3 for the channel discharge between the negatively charged artificial thunderstorm cell and the ground using the hydrometeor array.

C. Influence of hydrometeor array on the electromagnetic radiation of discharge between positive artificial thunderstorm cell and ground

As it has noted in [14] in the positively charged artificial thunderstorm cell the hydrometeor array could initiate the cloud discharges on the hydrometeor array (variant GMP1), the channel discharges between the cloud and the ground using the hydrometeor array (variant GMP2), and the diffuse discharges between the cloud and the ground using the hydrometeor array (variant GMP3).

Typical signals registered by the antennas during cloud discharges on the hydrometeor array have shown in Fig. 6.

Figure 6. Oscillograms of the signal registered by the plate antennas A1 (curve 2, shunt 0.5 Ohm), A2 (curve 3, shunt 0.5 Ohm), A3 (curve 4, shunt 0.5 Ohm) for cloud discharges on the hydrometeor array in the artificial thunderstorm cell of positive polarity.
The highest frequencies $f(C_{\text{MAX}})$ corresponding the maximal intensity $C_{\text{MAX}}$ in the wavelet spectrum and Fourier spectrum have observed for signals registered by the plate antenna A2 posed on the height of the hydrometeor array (Fig. 7). They could exceed one hundred megahertz. The corresponding frequency ranges for signals registered by the antennas A1 and A3 lie between 3 MHz and 12 MHz.

Variant GMP2 (formation of the channel discharges between the artificial thunderstorm cell of positive polarity and the ground with participation of the hydrometeor array) is characterized with the strong impulse current of the final stage and powerful electromagnetic radiation registered all three antennas (Fig. 8).

Analogous to the negative artificial thunderstorm cell, discharge processes on the hydrometeor array pass during some microseconds after the final stage ending and influence on the content of the electromagnetic radiation registered by the antennas. Typical wavelet spectrum of the signals registered by the antenna A2 for such discharges show some characteristic frequency ranges (Fig. 9): main range from some megahertz to some tens megahertz and secondary range from some tens megahertz to some hundreds megahertz. Broadband plate antennas A1 and A3 disposed on the ground obviously have only main range in the wavelet spectrum for registered signals.

Variant GMP3 (formation of the diffuse discharges between the artificial thunderstorm cell of positive polarity and the ground with participation of the hydrometeor array) is characterized with the relatively short impulse current of the final stage that has clear impulsive structure. Corresponding displacement current registered with all three antennas shows the impulse pockets before the beginning of the final stage current (Fig. 10). Wavelet spectrum of the diffuse discharge has more complicated character in comparison with the spectra of other discharges. One of the peculiarities is the presence in the spectrum of the electromagnetic radiation the characteristic frequencies up to 700 MHz in signal registered by the antenna A1, and up to 800 MHz in signal registered by the antenna A2. Antenna A1 has disposed on the ground in the immediate proximity from the place of the diffuse discharge formation. Antenna A2 has disposed on the level of the bottom boundary of the positively charged cloud where negative streamers develop from the upper hydrometeor in array.

Thus, wavelet spectrum of the electromagnetic radiation of the variant GMP3 has determined by the discharges between the hydrometeors in array, by the diffuse discharges between the bottom hydrometeor in array and the ground, by the negative streamer discharge between the upper hydrometeor in array and the positively charged artificial thunderstorm cell.
Oscillograms of the discharge current between the cloud and the ground (curve 1), of the signal registered by the plate antennas A1 (curve 2), A2 (curve 3), A3 (curve 4) for diffuse discharges on the hydrometeor array in the artificial thunderstorm cell of positive polarity.

III. DISCUSSION AND CONCLUSIONS

Thus, spectral characteristics of discharges developing in the gap “artificial thunderstorm cell – ground” with the participation of the hydrometeor array significantly depend on the cloud polarity. Analysis of the wavelet spectra of the electromagnetic radiation of the similar discharge phenomena (cloud and channel discharges) developing on the hydrometeor array disposed near bottom boundary of the artificial thunderstorm cell of negative or positive polarity has shown the following (Fig. 11 and Fig. 12).

More high characteristic frequencies for the case of negatively charged artificial thunderstorm cell have observed for plate antenna A3 (“far” ground plate antenna) in contrast to plate antenna A1 (“near” ground plate antenna) (Table I). Analysis of wavelet spectrum of the signal registered by the plate antenna A2 (disposed on the height of the hydrometeor array) has shown an inconsistent picture. For negatively charged cloud, upper level of the maximal frequency in the wavelet spectrum could exceed 1 GHz (for positive cloud, less than 800 MHz).

At the same time, average values of this parameter were close for negative and positive artificial thunderstorm cell. Upper level of the frequency of the maximal intensity in the wavelet spectrum of the electromagnetic radiation of the cloud and channel discharges on the hydrometeor array was high for negatively charged cloud for all three considered antennas (Table II).

Close average values have observed for the plate antenna A2 for the charged cloud of both polarities again. Probably, such dependence has connected with the peculiarities of discharge development between the neighbor hydrometeors in array.

### Table I. Spectral Characteristics of the Cloud and Channel Discharges on the Hydrometeor Array in the Artificial Thunderstorm Cell

<table>
<thead>
<tr>
<th>Plate antenna</th>
<th>Upper level of the maximal frequency in the wavelet spectrum (average value), MHz</th>
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<tbody>
<tr>
<td>Antenna A1</td>
<td>Negative cloud: 664 (107)</td>
</tr>
<tr>
<td>Antenna A2</td>
<td>Negative cloud: 2120 (420)</td>
</tr>
<tr>
<td>Antenna A3</td>
<td>Negative cloud: 970 (122)</td>
</tr>
</tbody>
</table>

Figure 11. Histograms of relative frequency of maximal frequency $f_{\text{MAX}}$ in the wavelet spectrum of signals registered by the antennas A1-A3 for channel and cloud discharges on the hydrometeor array in the negatively charged cell

Figure 12. Histograms of relative frequency of maximal frequency $f_{\text{MAX}}$ in the wavelet spectrum of signals registered by the antennas A1-A3 for channel and cloud discharges on the hydrometeor array in the positively charged cell
Another peculiarity in wavelet spectrum has found for frequency $f(C_{\text{MAX}})$ corresponding the maximal intensity $C_{\text{MAX}}$ in the wavelet spectrum for channel discharges on the hydrometeor array in the artificial thunderstorm cell of positive and negative polarity (Fig. 13). For signals registered by the antenna A3, frequency corresponding the maximal spectrum intensity was in enough narrow range between 5 MHz and 10 MHz for positive clouds (85%) and had much broad range for negative clouds (more than 10 MHz in 40% cases).

Thus, the arrays of large hydrometeors falling in the thunderstorm cell of positive or negative polarity probably could significantly influence on the frequency characteristics of cloud discharges [18] and discharges between the thundercloud and the ground and be the source of the super high frequency radiation up to 1-2 GHz registered with the lightning detection systems.

![Figure 13. Histograms of relative frequency of frequency $f(C_{\text{MAX}})$ corresponding the maximal intensity $C_{\text{MAX}}$ in the wavelet spectrum of the electromagnetic radiation registered by the antenna A3 for channel discharges on the hydrometeor array in the artificial thunderstorm cell of positive and negative polarity](image)

### Table II. Spectral Characteristics of the Signals Registered by the Antennas During the Cloud and Channel Discharges on the Hydrometeor Array in the Artificial Thunderstorm Cell

<table>
<thead>
<tr>
<th>Plate antenna</th>
<th>Upper level of the frequency of the maximal intensity in the wavelet spectrum (average value), MHz</th>
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<tbody>
<tr>
<td>Antenna A1</td>
<td>60.0 (11.0)</td>
</tr>
<tr>
<td>Antenna A2</td>
<td>300.0 (49.0)</td>
</tr>
<tr>
<td>Antenna A3</td>
<td>63.5 (15.6)</td>
</tr>
</tbody>
</table>

### References


