Rocket investigation of electrical characteristics of the thunderstorm clouds

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Abstract: The description of the equipment used according to the program of rocket sensing of electrical characteristics inside thunderstorm clouds in the Caucasus, with which the profiles of the three components of the electric field intensity in the cloud were measured, taking into account the influence of electrification currents flowing on the rocket probe in the thundercloud and the electric charge accumulated on it, is given. The coordinates of the trajectory of the sounding of the thunder cloud were measured and tied to the synchronously recorded radio echo of this cloud. Much attention was paid to justifying the reliability of measurements when creating a rocket probe. The description of one experiment on rocket sounding of the thunderstorm cloud is given as an example.

Introduction
Theoretical and experimental studies have shown that the actual electrical structure of these clouds cannot be established according to the results of measurements of electrical characteristics outside of thunderstorm clouds, which is important and necessary for understanding the basic processes leading to the development of thunderstorm phenomena. The electric field strength inside the clouds is one of their most important electrical characteristics. Information on the magnitude and intensity of the electric field and its space-time distribution, tied to the macro- and microphysical characteristics of the cloud, will help in understanding the physical bases of the electrical processes occurring in the cloud, the mechanism of lightning, protection of aircraft from lightning. This caused an urgent need to develop equipment and methods for measuring the electric field intensity inside a thundercloud [1 - 3]. The greatest interest are direct measurements of the electrical characteristics of the cloud by the method of their vertical sounding. For vertical sounding, a rocket radiotelemetry system (RTS) developed at the High-Mountain Geophysical Institute (HMGI) was used, which included a rocket probe, a receiving ground complex, and a monitoring and target selection equipment.

RTS hardware complex
The rocket probe is a modernized cloud-based anti-hail rocket, at the head of which scientific research equipment is installed to measure and transmit information on the electric field strength inside the cloud and other electrical parameters via a radio channel, as well as an active responder to accompany the probe and record the trajectory flight using radar 1B18 "Shkval". When creating a rocket probe, great attention was paid to the justification of measurement accuracy.

The rocket probe consists: electrical parameters sensors; information conversion devices; microwave transmitter; power supply unit onboard equipment. A cylindrical electrostatic fluxmeter of
the rotational type to measure three orthogonal components of the electric field strength is used. To
determine the field strength parallel to the axis of the rocket, it is measured at two points spaced along
the length of the rocket, which allows to take into account the rocket charge field. When measuring
perpendicular to the axis of the rocket, the components of the electric field intensity of the cloud
fluxmeter is not sensitive to the charge of the rocket. To measure the current density of static
electrification generated by the cloud aerosol bombardment rocket, the sensor is used, which is a
conducting measuring plate placed in the upper part of the rocket probe. For measurement of electric
charges of hydrometeors, induction rings are used as sensors.

The information conversion device (UPI-9K) provides amplification and conversion of signals
received from sensors of electrical parameters, and also encodes information for its transmission over
a radio channel to a ground receiving station. The upgraded meteorological radiosonde 1B25-2 is used
as a telemetric information transmitter. The detailed description of the rocket probe and its
metrological characteristics are given in [4].

The ground receiving complex of the rocket radio telemetry system [5] provides reception,
decryption and recording of information received over the radio channel from the rocket probe in
parallel through nine channels, as well as tracking the probe within a radius of 150 km with simultaneoun
registration of current coordinates. The ground receiving complex includes: radar 1B18
"Shkval"; information reception and conversion device (UPPI-9K); registration device; recording
device and playback information.

The upgraded "Shkval" 1B18 radar provides for receiving the microwave signal and extracting
telemetry video pulses, as well as autotracking along the coordinates of the “Oblako-M” research
rocket. The current coordinates of the radiosonde are recorded by the device “Shkval” 1B18 radar.
Registration speed is set from the radar automatic computing device console.

The device for receiving and converting information consists: an input device; pulse selector;
dercoder; switch; analog storage device; recording device; video monitoring device. In the input
device, the level of signals of radar 1B18 and UPPI-9k is coordinated. In the pulse selector, the input
telemetry information sequence is divided into channel and personnel sync pulses that control the
operation of channel switches and are simultaneously monitored by a video monitoring device.

The time intervals between channel pulses are converted into amplitude and polarity of the output
voltages in the decoder and analog storage device. The analog voltages from the output of the storage
device in parallel through nine channels are fed to the recording device. In the process of receiving
information from the radiosonde video pulses of telemetric information are recorded on the
information keeper.

The upgraded meteorological radar “Thunderstorm-26” is used to detect a cumulonimbus cloud,
measure its radar characteristics and select the zone of the cloud to be probed. The main characteristics
of the rocket radio telemetry system are given in the table.

| Characteristics of the missile radiotelemetry system (RTS) |
|----------------|----------------|----------------|----------------|----------------|
| Measured parameters | Range measurements | Measurement error | Sounding height |
| Ez, V/m | 10^5 – 10^6 | 17 % | to 8 km |
| Er, V/m | 10^2 – 10^4 | 10.5 % | |
| Q, C | 10^-7 – 10^-5 | 17 % | |
| jk, A/m^2 | 10^-7 – 10^-4 | 11 % | |
| q, C | 10^-11 – 10^-9 | 10 % | |

Note:
Ez, V/m - the vertical component of the electric field strength;
Er, V/m - the horizontal component of the electric field strength;
Q, C - charge on the rocket probe;
jk, A/m^2 - current density of static electrification;
The results of the experiment and the spatial-electric structure of the thunderstorm cloud

Complex experiments were carried out in the thunderstorm clouds, in which, simultaneously with the rocket sounding of the vertical profile of the three components of the electric field, the radar characteristics of thunderclouds were recorded. An analysis of the results of rocket sounding of these thunderstorm clouds showed that the profiles of the vertical component of the electric field strength vector in thunderstorm clouds are very diverse depending on the meteorological conditions of the area of origin of the cloud, the relative position systems of the main charges in the cloud and the trajectory of its sensing. As a result, it seems appropriate to analyze the experimentally obtained profiles of the electric field strength in thunderstorm clouds as a realization of a random process and to conclude that only those profiles obtained under similar conditions are comparable [6].

The measured electric field strength at each point along the probe path was considered as a random variable consisting of deterministic (created by main charges) and random (created by local fluctuations of the space charge density) components, and the profile of the vertical component of the electric field as a random process. To isolate the deterministic component of the profile, which was used to calculate the structure of the main electric charges, the measured profile of the vertical field component was smoothed. The smoothing interval was chosen from the requirement of smoothing the fluctuations and not smoothing the deterministic component of the profile of the vertical component of the electric field of the cloud.

The maximum values of the electric field intensity, measured over several years in thunderstorm clouds, in the active thunderstorm zone reach 1000 kV/m in volumes with a vertical length of 500 m and more and decrease sharply even with a relatively small distance from this zone. The highest values of the electric field strength are achieved in the zones located between the volumes occupied by the main charges of the cloud. In thunderstorm clouds usually form 2-3 main charge centers and a large number of mesoscale discontinuities. The mutual arrangement and the number of main charges depends, apparently, on the stage and individual features of the cloud development.

According to the profile of the deterministic component of the vertical component of the electric field, you can determine the number, signs, of radius spheres and the height of the main electrical charges in the cloud. Since rocket sounding of the electric field was carried out synchronously with radar observations and recording of the radio echo in the reflectivity isocontours, when the sensing trajectory is superimposed on the radio echo pattern, the structure of the main electrical charges turns out to be tied to the microphysical and geometric structure of the cloud. By approximating the main electric charges of the cloud by uniformly charged spheres (or ellipsoids, etc.), the diameter of which is equal to the distance between two bends the profile of the deterministic component of the vertical component of the electric field Ez, it is possible to calculate the magnitudes of these charges.

For a thundercloud model with three main charge centers, where the top positive charge is located at the top, the average negative charge is in the middle and the bottom positive charge is at the bottom [7]. The profile of the vertical component of the electric field strength Ez along the height near the vertical connecting these charges will look like a broken curve, which indicates the presence in the cloud of several main charges of different signs:

- the number of main charges in the cloud is one less than the number of extreme points on the graph of the vertical course of the Ez values;
- charge centers are located in horizontal planes equidistant from extreme points of the graph Ez;
- the diameters of the spheres occupied by the charges are equal to the distance between horizontal planes passing through the extremes Ez value profile;
- the signs of charges are indicated by the nature of the change in Ez (z), if during movement up the z axis, the field strength Ez (z) changes from positive to negative values, then the crossed charge is positive, with the opposite the nature of the transition is negative.
According to the profile of the vertical component of the electric field, obtained in the course of the experiment, using the Poisson equation, you can find the magnitude of the main space charges, if we ignore the horizontal components of the electric field: $\rho = \frac{1}{\varepsilon_0} \frac{\partial E}{\partial z}$, where $\rho$ is the space charge density, $E$ is the electric field strength, $z$ is the height. The values of the main charges are calculated from the measured distribution of the vertical component of the electric field strength $E_z$. Hence, using the solution of the Poisson equation for a uniformly charged sphere of radius $R$, the electric field strength along the vertical axis $z$ inside the sphere will have the form for our case:

$$E_{zi} = \frac{Q_i z_i}{4\pi\varepsilon_0 R_i^3}, \quad |z_i| \leq R_i$$  \hspace{1cm} (1)

For the electric field strength outside a uniformly charged sphere, we can replace the field of a point charge equal to the charge of the sphere and located in the center of the sphere and will have the form for our case:

$$E_{zi} = \frac{Q_i}{4\pi\varepsilon_0 z_i^2}, \quad |z_i| \geq R_i$$  \hspace{1cm} (2)

where $Q_i$ is the value of the $i$-th main charge; $R_i$ is the radius of the $i$-th sphere; $z_i$ is the height along the $z$ axis from the center of the $i$-th sphere; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m is the electric constant.

Based on (1) and (2), for the structure of three centers of charges – $Q_1$, $Q_2$, $Q_3$, a system of three equations is constructed, with respect to these charges, for arbitrary points A, B, C, on the measurement trajectory taking into account the signs of charges and the principle of superposition, an electrostatic calculation is made and the values of the main charges of the thundercloud are determined.

As an example, Figure 1 shows the experimental course of the vertical component of the electric field strength $E_z$, on the basis of which the electrical structure of the main charges is determined and the values of the main charges for a thundercloud at the stage of maturity for June 18, 1987 are calculated, where the electric intensity $E_z$ field reaches more than 200 kV/m and in the cloud there are three main charge centers:

![Figure 1. The structure of the main electric charges and the course of the vertical components of the electric field of a thundercloud for June 18, 1987](image-url)
- the bottom positive charge is $Q_1 = +7 \text{ C}$, occupies a volume with a radius $R_1 = 0.5 \times 10^3 \text{ m}$ and the center of charge at a height of $h_1 = 2.7 \times 10^3 \text{ m}$;
- average negative charge $Q_2 = -18 \text{ C}$, occupies a volume with a radius $R_2 = 1.5 \times 10^3 \text{ m}$, and the charge center at height $h_2 = 4.8 \times 10^3 \text{ m}$;
- top positive charge $Q_3 = +1 \text{ C}$, occupies a volume with a radius $R_3 = 0.3 \times 10^3 \text{ m}$ and the charge center at a height of $h_3 = 6.7 \times 10^3 \text{ m}$;

It is obvious that the volumes occupied by the main charges do not have a regular geometric shape and the space charge is not strictly uniformly distributed in them, the charge centers were not strictly located, the probing trajectory passed along the centers of these charges as close as possible. However, such assumptions cannot, in our opinion, introduce significant distortions in solving the problem of determining the macro-electric structure of thunderclouds.

Summary
Rocket soundings made it possible to clarify the magnitudes of the electric field strength characteristic of the active zone of thunderstorm clouds, they turned out to be equal to $(100 - 200) \text{ kV/m}$ and more. Zones with such intensity may have a vertical length of $500 \text{ m}$ or more. According to the results of measuring the vertical component of the electric field strength in thunderclouds, one can estimate the spatial structure and calculate, based on a simple model, the magnitude of the main volume charges of thunderclouds. For a sufficiently accurate parameterization and the construction of the most appropriate model for the formation of the electrical structure of clouds, we need, in our opinion, the accumulation of a large number of systematic measurements carried out in different physical-geographic and weather conditions.

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