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A highly efficient calibration method for the localization of point sources of microwave radiation

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Methodology of localization with centimeter accuracy of a gigahertz radio emission source generated by a known point source using four ultra-wideband antennas is described. Localization is performed by calculating the spatial location of the first burst of the microwave generator.

Keywords: radio emission, triangulation, atmospheric spark discharge.

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An ultra-wideband antenna designed and modeled for use in experimental research into radio emission generated in the initial phase of a spark discharge was presented in our earlier study [1]. It was demonstrated there that the highest-frequency part of the radio spectrum of a spark discharge corresponds to the pre-breakdown stage of its development. The generation times of radio emission at frequencies of 1 − 6 GHz are on the order of nanoseconds, and radio emission is recorded in the form of several bursts. The authors of [2–4] observed microwave pulses with frequencies of 1.5 − 1.6 and 2.4 GHz. Processes inducing microwave generation were discussed in [5–8], and the possibility of localization of sources of microwave radiation generated in the initial phase of a high-current atmospheric spark discharge was demonstrated.

In the present study, we detail the methods used to set up and test the microwave localization system presented in [5]. In calibration experiments, the radio recording system was tested by localizing microwave radiation generated by a compact microwave generator producing voltage pulses with an amplitude of approximately 10 kV and a current lower than 1 mA (Fig. 1). The high-voltage section of the custom microwave generator is diode cascade high-voltage generator *1*. It is compound-filled and has an elongated cylindrical shape. The generator was powered by 6 V lithium battery *2* and was discharged into 10-mm-wide spark gap *4* on the press of button *3*. In order to reduce the possible uncertainty in determining the location of emission regions, the spark gap was positioned near the region of geometric center *5* of the microwave generator (its resulting dimensions are $7 \times 3.5 \times 4$ cm). All generator contacts connected by wires *6* were insulated, and the generator itself was mounted on dielectric table *7* in the center of the studied discharge gap and far from the metal electrodes [9–11]. This was done to suppress dipole radiation that could be induced by the generator on any nearby metal surface and could distort individual bursts of microwave radiation used for localization. Dielectric table *7* was, in turn, secured to a micrometer-precision translation stage. The generation of microwave radiation lasts for about 400 ns at frequencies up to 6 GHz, and the radiation power is maximized within the 1 − 2.5 GHz frequency band.

The used Vivaldi antennas with linear polarization were mounted on dielectric stands at different distances in the „far field“ from the discharge gap center and detected microwave radiation with certain delays (Fig. 2, *b*). These antennas were adjusted so that their main beams were directed at the discharge gap center and the polarization of each antenna was approximately co-directional with the discharge gap axis. The spatial positions of antennas were measured with an accuracy of 0.5 cm. All delays within each antenna and delays in each of the signal paths were taken into account In signal synchronization.

The signal received from the antennas was recorded by a LeCroy WM 8620A oscilloscope with a bandwidth of 6 GHz and a minimum sampling time of 50 ps. The oscilloscope was installed in a screened room and connected to the antennas with low-loss 9-m-long SF-141 FEP cables (with attenuation below 1.1 dB/m at frequencies lower than 6 GHz). Owing to their small amplitude, microwave signals were recorded without attenuators. An important feature of these signals was that the examined rise time between the first point and the first peak of the very first packet was close to 100 ps, and the increase in signal amplitude was more than an order of magnitude greater than the noise level. The difference in amplitudes of the first half-period of signals is attributable not only to the positioning of the antennas at different distances from the source, but also to the specifics of the directional pattern of the source. When two antennas (e.g., antennas 3 and 4) were swapped in position, the signal amplitude from the antenna in position 3 remained approximately 1.5 times higher than the one corresponding to the other antennas.

A special technique based on the analysis of spectral and temporal characteristics of signals recorded in parallel was developed in order to identify and localize a single burst in

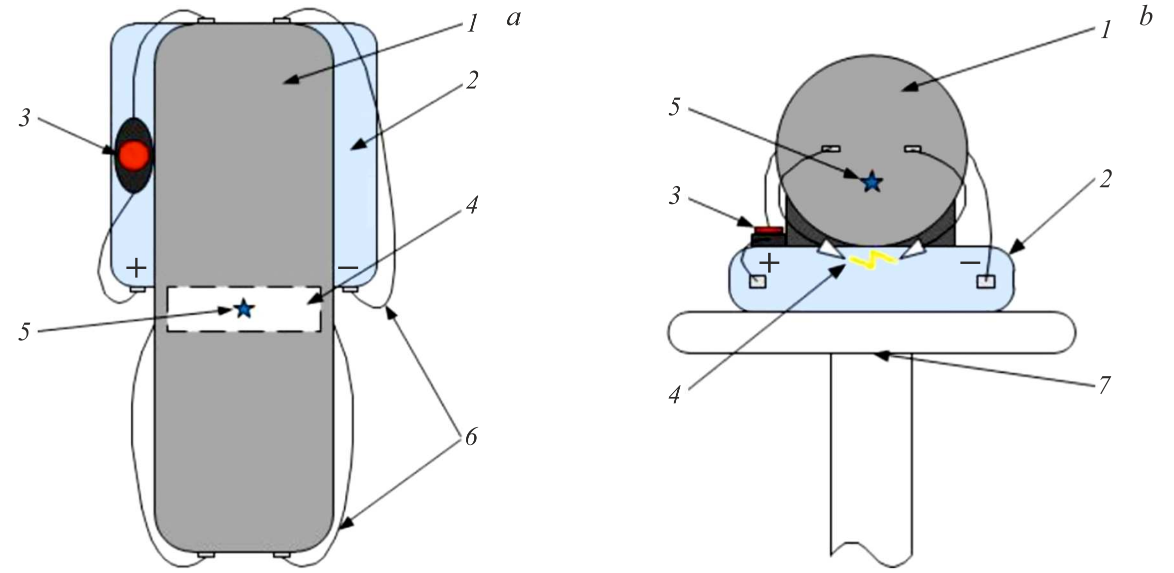

Figure 1. Schematic diagram of a microwave generator. *a* — Top view; *b* — side view. See explanation in the text.

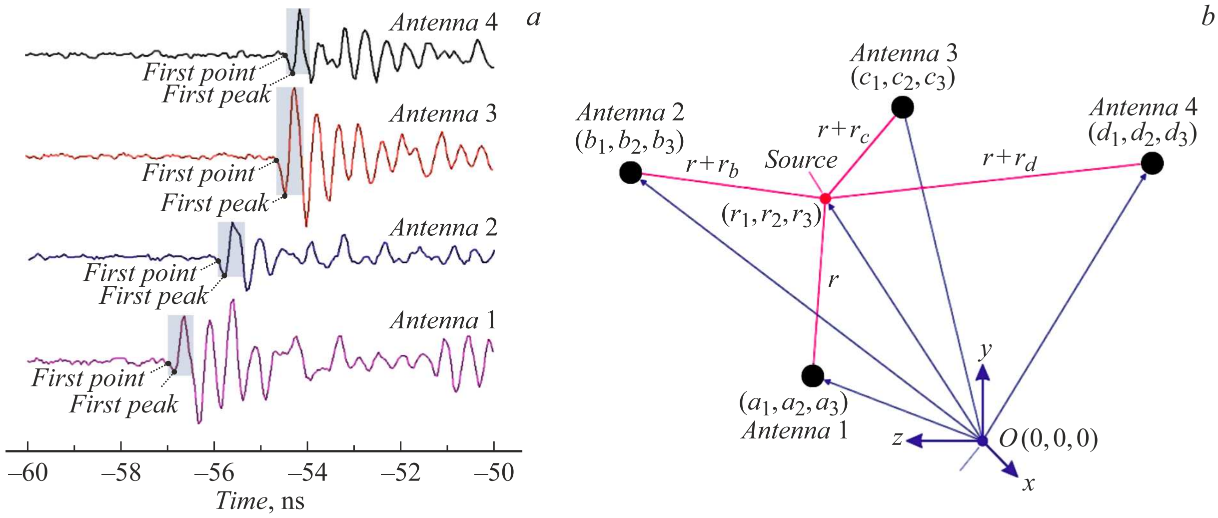

Figure 2. Typical microwave signal (*a*) and diagram of the localization complex (*b*).

microwave signals. According to this method, the first point above the noise level should be found for the very first burst on the curve of each useful signal. Its absolute amplitude is taken to be equal to the maximum amplitude of signal oscillations before the onset of microwave emission (see the origin of the signal in Fig. 2, *a*). Starting from the first point, the key patterns of signal oscillations are examined within an interval of approximately 1 ns. These patterns (e.g., front polarity and pulse duration) should be correlated in all four signals received from the antennas.

The inverse localization problem was solved (Fig. 2, *b*) to determine the exact position of the microwave radio source. It is assumed that the source is a point dipole (a point with coordinates r_1, r_2, and r_3); distance r from the source to the first antenna is the unknown quantity. Since antenna 1 is the closest to the source, the signal at it is always observed earlier than at the other antennas. Thus, if the exact positions of all four antennas in a given coordinate system and the relative time delays between the signals from each antenna are known, the localization problem (finding the value of r) may be reduced to solving a system of linear equations. The solution is a point at which the point source should be located.

Five series of 50 events were examined in the calibration experiments (Fig. 3). Plane XZ is the horizontal plane of the studied discharge gap [5]. Axis X is the discharge gap axis with a length of 55 cm. In each series of calibration experiments, the microwave generator elongated along axis Z had the same position along vertical axis Y. The geometric center of the generator moved in horizontal

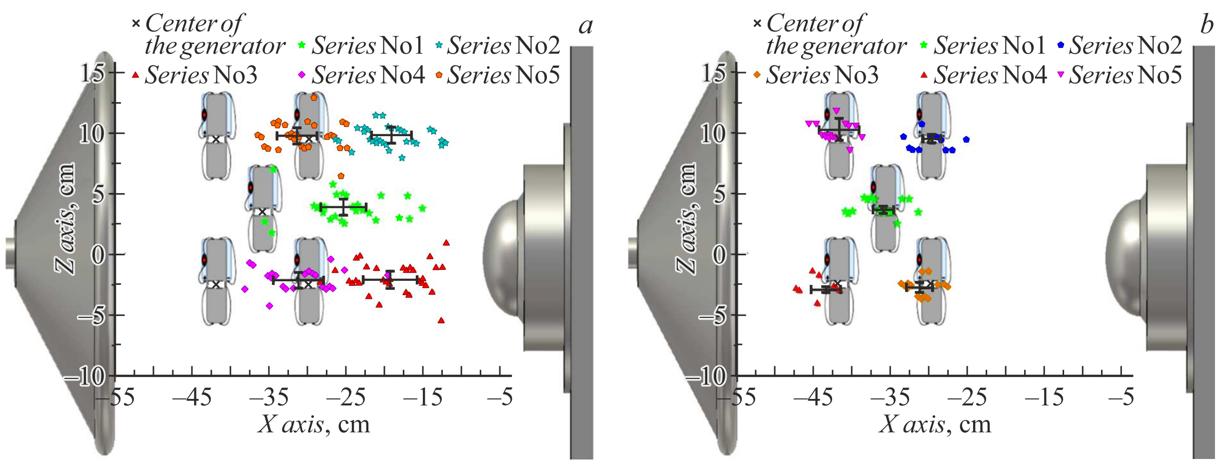

Figure 3. Microwave radiation sources localized in five series of 50 events (a) by the point of emergence from noise with no systematic error correction and (b) by the maximum point of the burst with systematic error correction.

plane XZ in different directions for a distance of 6 cm relative to the central position. These positions are sufficient to verify the reliability of source localization in the discharge gap regions where plasma microwave sources are likely to be localized. Each point in the XZ plane is associated with the very first burst identified in microwave radiation signals. The positions of statistical centers of localized sources and their standard deviations along the main coordinate axes were determined for each series. When testing the localization method, we tried two methods of selection of points within the studied burst. In the first case, we took the point following the emergence from noise (Fig. 3, a). In the second case, the point of the first maximum/minimum for four correlated bursts was taken. The second method was the preferred one, since, statistically, it allows for more precise localization of the source and the points are grouped more closely.

It can be seen From Fig. 3 that even with preliminary calibration of all signal paths (with an error of 100 ps) and antenna positions (with an error of 0.5 cm), the localization accuracy in determining the emission regions is quite good (on the scale of the entire setup). All localized sources are within the generator height (the deviation does not exceed 4 cm). Here, the mean standard deviation of positions of sources from their statistical centers does not exceed 2 cm in all five series.

The greatest spread of source positions is observed along the X axis. Notably, the statistical centers of localized sources in all series do not coincide with the geometric center of the microwave generator. Each statistical center is located approximately 13 cm away from the geometric center, which is indicative of a certain systematic error in solving the localization problem. This error may be caused by the spread of delays in signal transmission paths, which cannot be measured with an accuracy greater than the one set in the calibration experiments.

The essence of the problem of systematic error control is as follows. Knowing the coordinates (x, y, z) of the geometric center of the microwave radiation source (which, as calculations have shown, coincides with the geometric center of the generator in Figs. 1 and 3), the antenna coordinates (x_i, y_i, z_i), and relative time delays Δt_{ij} (i, $j = 1{-}4$) between the signals recorded in 50 events, one may determine statistical corrections σ_{ij} to delays Δt_{ij}. Corrections σ_{ij} include all unknown variations in signal paths and antenna coordinates. In mathematical terms, this problem is solved by minimizing each of the six expressions with the use of the RMS function that tends to zero. Thus, we found that the best fit between the positions of statistical centers of microwave radiation sources and the center of the microwave generator in all five experimental series was obtained at $\sigma_{12} = -40$ ps, $\sigma_{13} = -55$ ps, and $\sigma_{14} \approx 0$ ps. The results with these corrections introduced are presented in Fig. 3, b. The assumption that the most probable emission region coincides with the geometric center of the microwave generator turned out to be the optimum one in all series.

Thus, methods for calibrating the diagnostic equipment designed for localization of microwave bursts of the centimeter range with a compact microwave generator were presented. A technique for correcting the statistical error arising in localization of the source coordinates was presented. It may be concluded that the presented method is suitable for calibrating the diagnostic radio recording system and that the obtained results are consistent with theoretical assumptions and other diagnostic data. The discussed methods will be used in comprehensive research into the generation of microwave radiation from a high-voltage atmospheric spark discharge, which should provide a deeper insight into fundamental processes occurring at the initial discharge stage.

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Conflict of interest

The authors declare that they have no conflict of interest.

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